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THE BREEDING OF DISEASE-RESISTANT VARIETIES OF OATS

Pt. II. INHERITANCE OF DISEASE-RESISTANCE

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The fundamental researches conducted by plant pathologists leading to the discovery of physiological races and to a fuller understanding of their nature, behaviour, and culture, have enabled considerable advances to be made in the study of the mode of inheritance of resistance to fungal diseases. The earlier observations in the study of disease-resistance were, however, somewhat conflicting, and doubts were expressed as to the stability of the resistance character since it still remained uncertain whether resistance was or was not largely dependent on climatic and cultural conditions; varieties resistant to disease in one locality, or under one set of climatic conditions, were observed to be susceptible when grown in another locality, or in a different season or set of environmental conditions. Researches on physiologic specialization and on the influence of environmental and other conditions, using host-plants experimentally inoculated, have elucidated some of the causes of the apparent instability. These studies have shown that certain physiologic races of stem rust and of crown rust may vary in their infection types on some host varieties when incubated at low and high temperatures, whilst other races and host-plants show a more consistent behaviour [27, 28, 29, 23]. The occasional apparent breakdown of resistance to rusts and smuts in the field may be due to contamination of the resistant variety by accidental admixture with seed of a susceptible variety, to segregation following natural crossing with a susceptible variety, or to the resistant variety on being grown in a new area becoming infected by a physiologic race to which it is inherently susceptible [21]. There is, however, the rare possibility that a disease-resistant variety may, under exceptionally favourable conditions, succumb to a race of smut that does not ordinarily attack it [68]. New physiologic races arise from time to time, and mutations may occur [26], but there is no evidence that such mutations appear more frequently than do mutations in other plant species. In all these studies there is no specific evidence that host reactions and parasitic behaviour do not conform closely with known and accepted biological principles. More data are required, however, on the effects, if any, of competition between physiologic races and its probable influence on the prevalence of rare races in a given region subsequent to the introduction of varieties resistant to the prevalent races but susceptible to those that are rare. On this problem information is being accumulated following the introduction of resistant varieties and their extended cultivation.

It is well to make clear that the term 'resistant variety' is frequently used in a limited sense, and is rarely meant to imply resistance to all physiologic races of a particular parasite. It is commonly applied to varieties that are resistant to the most prevalent physiologic races in the area where the variety is normally grown, or to a specified number of

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physiologic races. There are, however, a few varieties of oats, e.g. Victoria, Navarro, and Markton, that are resistant to all, or very nearly all, the known physiologic races of both loose and covered smuts [32, 33, 69], but there is at present only one selection, namely, R.L. 811 (Hajira × Joanette strain), synthetically produced, which is resistant to all the known races of stem rust, with the exception of Race 6 at high temperature, although there are three others of related parentage that are described as moderately resistant to some of the races and fully resistant to the remainder [70, 71]. No plants have been found that are resistant to all the known races of crown rust, but the varieties Victoria and Bond possess resistance to a very large number. Most cultivated varieties of oats are susceptible to many, or all, of the physiologic races of parasitic fungi.

As a result of comparatively recent researches in North America much information of immense value to breeders is now available on the reactions of many cultivated varieties and other species of oats to many, or all, of the physiologic races of loose and covered smuts [72, 73, 68, 74, 32, 69], of stem rust [12, 75, 14, 71], and of crown rust [21, 76, 23], as well as on the reactions of new hybrid varieties possessing a high degree of resistance to two or more of these fungal species [77, 1, 78].

By treatment with composite inoculum or single-spore cultures for the artificial infection of the segregates, the mode of inheritance of disease-resistance has been studied in a large number of crosses between resistant and susceptible varieties of oats. Numerous papers have been published, but only the principal findings of some of these need be considered here. These researches have been chiefly concerned with the inheritance of resistance to loose and covered smuts, to stem and crown rust, and with the presence or absence of any correlation between susceptibility to these diseases and morphological characters of agricultural importance.

Inheritance of Resistance to Loose and Covered Smuts

In making a genetical analysis of inheritance of resistance to smut in hybrid material, the proportion of resistant and susceptible plants is determined by inoculation tests of the F_2 generation, followed by supplementary tests in F_3 of plants showing negative reactions in F_2. Since those F_2 plants giving positive reactions produce no seed, it is necessary, when a detailed factorial analysis is required, to grow a parallel series of F_2 plants raised from uninoculated seed. It is a general practice to base the classification of the F_3 families on the percentage frequency of susceptible plants in each family. These frequencies are, however, affected to some extent, as well as those of the F_2, by the efficiency of the inoculation technique and the influence of environmental conditions at the early stages of seedling development. Confirmation of the F_3 results is, therefore, generally necessary by making progeny tests at least of some of the families in F_4. Control inoculations using pure-line material of both parental varieties are usually made in conjunction with each separate test of the hybrid generations.

Quite frequently plants belonging to a variety susceptible to certain physiologic races give a high degree of infection, up to 100 per cent. [79, 80], when the dehulled grain is dusted with a spore inoculum of a single

race, or mixture of the races, to which the variety is known to be susceptible. Inheritance studies, when such varieties are used as parents, are generally fairly straightforward. Other varieties of known susceptibility regularly give a characteristically lower percentage infection to certain races, even when all precautions are taken to ensure optimum conditions of moisture and temperature when the treated seed is sown [32, 81, 82]. Resistant varieties when artificially inoculated generally give an entirely negative result, but in a few varieties occasional smutted heads may be produced. Factorial analysis of inheritance in crosses in such varieties is, therefore, more difficult to elucidate. Owing to the observed varietal differences in degree of infection the experimental data, as would be expected, show differences in mode of inheritance, depending on the varieties intercrossed.

In most inheritance studies with loose and covered smuts [83, 84, 85, 82, 86, 87], resistance, with few exceptions, has been found to behave as a dominant character. Segregation in many cases occurs on a monofactorial basis and no close linkage has been observed between resistance to smut and undesirable agronomic characters of the panicle and grain. Dihybrid segregation for resistance to covered smut has been observed by Johnson [88] to occur in the cross Black Mesdag (resistant) × Victory (susceptible). Garber *et al.* [89] interpreted the mode of inheritance in Black Mesdag × Gopher (susceptible) on the basis of one gene for resistance carried by Black Mesdag and an inhibitor gene carried by Gopher. In other cases segregation is more complex and approximates to a three-factor basis [90, 73]. Transgressive segregation has been observed by Coffman *et al.* [81] and Garber *et al.* [91] in which some susceptible F_3 families showed a higher percentage infection than the susceptible parent.

Reed [84] in the cross Hull-less × Black Mesdag found a close parallelism in the reaction to the loose and covered smuts respectively which indicated that either a high degree of linkage was present or that the same factor was responsible for resistance to both kinds of smut in the Black Mesdag parent. Segregation for both smuts showed approximate agreement to expectation on a monohybrid basis. In crosses between Markton (resistant to loose and covered smuts) and the susceptible varieties Canadian, Early Champion, and Victor, Reed and Stanton [80] observed the inheritance of the reactions to loose and covered smuts to be entirely independent of one another, indicating correspondence with a dihybrid segregation for loose smut and a single factor segregation for covered smut. In the cross Monarch (susceptible to covered, but resistant to loose, smut) × Markton, segregation for resistance to covered smut occurred on a single-factor basis, but a few F_2 plants showed susceptibility to loose smut. The number of F_3 families susceptible to covered smut was, however, fewer than the theoretical expectation. In the cross Gothland (susceptible to loose smut) × Markton, the segregation for loose smut conformed in a general manner to a single factor difference, but there was an absence of completely susceptible F_3 families. As a result of these and other studies Reed and Stanton considered that Markton probably carries a factor, or factors, which prevents

the full expression of susceptibility in the offspring of crosses between it and varieties susceptible to smut. In the hybrid offspring of Early Gothland (resistant to covered and susceptible to loose smut) × Monarch (susceptible to covered and resistant to loose smut) inoculated with Missouri races of loose and covered smuts, Reed [92] obtained independent inheritance of the two kinds of smut. Several F_3 progenies were resistant to covered and susceptible to or segregating for, loose smut; others were resistant to loose smut and susceptible to or segregating for covered smut, and a third group of families was resistant to both loose and covered smuts. No progenies were obtained that were entirely susceptible to both smuts. The absence of this class may have been due to their elimination in F_2, but no clarification of this point was obtained by a further, but limited, investigation of 30 families derived from uninoculated F_2 plants.

Of main importance to the plant-breeder in these studies of inheritance are the facts that resistance to both loose and covered smuts can, by crossing, be combined in one variety; that resistance normally behaves as a dominant character and exhibits Mendelian inheritance; and that by hybridization it is possible to obtain combinations of resistance to both kinds of smut, with varietal characters of a desirable agronomic type. Although there are several physiologic races of both kinds of smut, to one or more of which one variety of oats may be susceptible and another resistant, the breeding problem is simplified in that the inheritance of resistance to one or several physiologic races of smut is frequently determined by a single major gene, occasionally by two factors, and only rarely is the inheritance of a highly complex nature.

Inheritance of Resistance to Stem and Crown Rusts

Studies of the inheritance of resistance to stem and crown rusts are in general somewhat simpler and less laborious to investigate than their counterparts in the smuts. Infection reaction can be determined by inoculation of the seedling leaves, and since the seedling reactions in most cases agree closely with those of the adult plant [14, 23, 93], it is not essential to carry the plants to the mature stage unless supplementary F_3 observations are required to verify the classification of doubtful cases. Large numbers of F_2 seedlings can in consequence be easily handled, in batches if necessary, within the confines of a relatively small greenhouse, and only those individuals showing indeterminate reactions need be grown to produce seed for supplementary investigations. In any case, the relative ease and rapidity with which the study of F_3 as well as that of the F_2 seedlings can be carried out under greenhouse conditions, using controlled temperature and light, permit of large numbers being handled with a minimum of labour. If necessary, each seedling plant may be tested with more than one physiologic race culture by separate inoculation of individual leaves. Whilst plants giving resistant reactions in the seedling stage vary little in their rust reactions with age, susceptible seedlings may not always be equally susceptible in the adult stage [23].

Stem rust.—In a study of the varietal resistance of 27 varieties and strains of oats to stem rust, Levine and Smith [14] distinguished 4 main

groups on the basis of their reactions to different physiologic races, viz. (*a*) White Tartar, Green Mountain, Minrus, Minnesota 742, and Anthony, which are moderately resistant to Races 1, 2, 5, 8, 9, and 10; (*b*) Richland, Rainbow, Iogold, Hawkeye, Iowa D67, and Hajira, which are very resistant to Races 1, 2, 3, 5, and 7, give mesothetic reactions to Race 9, and are very susceptible to Races 4, 6, 8, and 10; (*c*) Joanette strain and Sevnothree, which are extremely resistant to Races 1, 3, and 4, give mesothetic reactions to Races 5 and 10 and are completely susceptible to Races 2, 6, 7, 8, and 9; the infection types in this group are sensitive to changes of light intensity and Races 5 and 10 in particular to changes of temperature; (*d*) varieties susceptible to all physiologic races. With the exception of Race 9 in Group (*b*) no significant deviations from normal infection types are developed by members of Groups (*a*), (*b*), and (*d*) when inoculated at high, medium, or low temperature.

The Joanette strain is reported by Welsh [70] to be resistant at low temperature to Races 1, 3, 4, and 10, and to give an indeterminate reaction to Race 5. By crossing the Joanette strain with Hajira strain Welsh has been able to isolate a number of resistant lines, including one (R.L. 811, already mentioned) that is resistant to all the known races of stem rust. The unexpected appearance in this cross of resistance to Race 6 to which both parents are susceptible he ascribes to transgressive segregation. At high temperatures (75° to 80° F.) there is, however, a breakdown of resistance to Race 6, and an indeterminate reaction to infection by Races 1, 4, and 5. Gordon [28] has shown that the Joanette strain gives a heterogeneous reaction to Races 1, 3, 4, and 5, being resistant to Races 1, 3, and 4 when the seedling plants are incubated at 60·8° F., and susceptible of producing heterogeneous reactions when kept at high temperatures (76·8° F.).

In later work conducted by Newton, Johnson, and Peturson [71] on the seedling reactions to stem rust of 78 oat varieties and hybrid selections, most of the varieties were observed to be susceptible to the 11 races used in the tests. Members belonging to the Richland group were resistant to Races 1, 2, 3, 5, 7, and 12, and of the White Tartar group moderately resistant to Races 1, 2, 5, 8, 10, and 10*a*. The Joanette strain and Sevnothree were resistant to Races 1, 3, 4, and 10*a*, and moderately resistant to Races 5, 12, and 13. Of the hybrid strains bred by Welsh, R.L. 811 showed resistance to all races and 3 sister strains showed resistance to all races except Race 6, to which race they were moderately resistant. Five hybrid selections derived from Hajira × Banner and Victoria × (Hajira × Banner) were resistant to all except Race 6, to which race they were susceptible, or moderately susceptible.

Garber [94] in a study of the inheritance of reactions to stem rust obtained simple Mendelian segregation with resistance dominant in the crosses White Russian × Minota and White Russian × Victory; Dietz [95] obtained similar results in crosses between White Tartar and the susceptible varieties National and Lincoln. In other studies in which Dietz crossed White Russian (a synonym of White Tartar) with 3 genetically different strains of Burt (*A. byzantina*), each of the 3 crosses behaved in a different manner. In one of them the F_1 plants were susceptible and

gave a ratio of 13 susceptible to 3 resistant in the F_2. These results were explained by Dietz on the basis of one factor for resistance carried by White Russian and a factor carried by the Burt parent which acts as an inhibitor of resistance in the hybrids. Resistance was observed to be dominant in the F_1 of the second Burt strain, and the F_2 consisted of resistant and susceptible plants in a ratio of 3:1. In the third cross susceptibility was dominant, and resistant and susceptible plants occurred in the F_2 in the ratio of 1:3.

Welsh [96] and Gordon and Welsh [18] report simple segregation in the cross Hajira × Banner (susceptible) with resistance dominant, the resistant reaction of the Hajira parent to the physiologic Races 1, 2, 3, 5, and 7 behaving in inheritance as a single group. This same variety when crossed with Joanette strain (resistant to Race 4) showed simple and independent inheritance of resistance to Race 4 in relation to the single-group inheritance in respect of Races 1, 2, 3, 5, and 7. Smith [97] obtained evidence that resistance of the White Russian type to Races 1, 2, and 5 was allelic to the resistance of Rainbow to Races 1, 2, 3, 5, and 7.

Crown rust.—In studies of the inheritance of resistance to crown rust Davies and Jones [98, 99] obtained simple segregation in a cross between resistant Red Rustproof (*A. byzantina*) and susceptible Scotch Potato (*A. sativa*), resistance behaving as a dominant character. Parker [100] in the F_2 of resistant Burt × Sixty Day (susceptible) obtained a complex segregation with a high proportion of susceptible plants. Torrie [93] in a cross Iowa No. 144 × Bond reports the occurrence of two factors: *S*, a factor for crown-rust resistance, and *I*, a factor which partially inhibits the expression of *S*. He also found that inoculations made with individual physiologic races gave similar results to inoculations with a composite inoculum, indicating that in the Bond parent resistance to several physiologic races behaves as a single unit in inheritance. Murphy *et al.* [77] reported that Bond is highly resistant to 48 of the 51 races of crown rust known to occur in North America. Later studies [1] have shown that this variety is immune from 75 of the 82 physiologic races of crown rust, resistance to all of which is controlled by a single major gene.

Recent Progress in Breeding Resistant Varieties

Torrie has shown that resistance to smut, stem rust, and crown rust are independently inherited and also give independent segregation with the agronomic characters, earliness of maturity, spikelet articulation, and basal hair-length of the grain. Other workers [101, 102] with crosses between Bond and varieties of *Avena sativa* record the possibility of combining resistance to these three major diseases in segregates of a desirable agricultural character. Confirmation of this is provided by the co-operative efforts of Murphy, Stanton, Coffman, and other U.S.A. breeders in the development of the new high-yielding varieties Vicland, Tama, Boone, Cedar, Control, and Vikota from the cross Victoria × Richland, made by Stanton in 1930 [1, 103]. These are early maturing varieties and are described as having short, stiff straw and plump yellow grain combined with a high degree of resistance to loose and covered smuts and to stem and crown rusts. The Victoria strain used in this

cross is resistant to all but 6 of the 82 races of crown rust, to 29 of the 31 races of loose smut, and to all the known races of covered smut [1]. Unfortunately the Victoria parent is susceptible to attack by *Helminthosporium victoriae*, susceptibility to which is said to be completely linked with the 'Victoria type' of resistance to crown rust [104]. In consequence, these new varieties are all susceptible to attack by this fungus.

A further series of new oat varieties has, however, more recently been introduced in the U.S.A. derived from the cross D.69 × Bond (made by Murphy in 1932) which, although susceptible to Race 45 crown rust, and to Races 8 and 10 of stem rust, are highly resistant to most of the prevailing races of stem and crown rusts and smuts in the U.S.A., and are immune from attack by *H. victoriae*. Of these, Clinton and Benton have already been placed on the market, and other varieties, such as Eaton, Bonda, Mindo, Camellia, &c., are in course of multiplication and distribution. These new varieties represent an important advance in the breeding of oats for resistance to fungal diseases, and possess valuable economic characters, such as high yield, improved quality of grain, and a high degree of resistance to lodging [78, 105]. In addition to their immediate economic importance as varieties for cultivation in those regions of the Corn Belt area of the U.S.A. to which they are ecologically adapted, they provide gene combinations of value to oat-breeders in other regions which may be used for crossing with local varieties where earlier or later maturing varieties of a somewhat different agronomic type are needed. Although these new productions are not resistant to all of the prevailing races of smuts, crown rust, and stem rust, further crosses can and have been made designed to incorporate resistance to other economically important races. The battle against disease is a slow and continuous process inasmuch as any new physiologic races which may appear from time to time provide a potential threat to the newly produced resistant variety. The rapid strides that have been made in the past two decades are, however, highly encouraging and give promise of further advances in the near future. These new synthetic productions have been largely due to the discovery in 1929 at Ames, Iowa [1], of the varieties Victoria, and especially Bond, which amongst a collection of no less than 1,500 varieties and selections were observed to be outstanding in their resistance to crown rust. Their speedy development owes a great deal to the painstaking researches of pathologists working in collaboration with the breeder in the study of parasitic disease.

Breeding Technique

Cultivated oats, as already indicated, are subject to injury by several kinds of parasites and only a relatively small number of the older varieties, mainly members of the red-oat group (*A. byzantina*), are found to be resistant to more than one kind of parasitic fungus, and of these few or none possess resistance to all the physiologic races of any one parasitic species. For this reason synthetic breeding by the intercrossing of selected resistant varieties is necessary in order to develop and combine in one variety resistance to the maximum possible number of

parasitic diseases. To do this systematically a knowledge of the characteristics and mode of inheritance of disease-resistance is necessary, and investigations have to be made of the disease-reactions of existing varieties so as to be able to select the requisite kinds of resistant plants to be used as parents in any specific geographical area. All too frequently the locally grown varieties may be susceptible to the major plant diseases, in which case search for resistant parents has to be extended to land varieties and to varieties and species selected from foreign sources. To this end the reactions of the widest possible assortment of varieties should be closely studied.

As a first objective the synthetic-breeding programme may be directed to combining in one variety, or in a few suitably adapted agronomic varieties, a high degree of resistance to those diseases of greatest importance in the area in which the improved varieties are to be grown. So long as there is available a source of adequate resistance to the physiologic races of the main parasitic fungi prevailing in any given region, and this appears to be so in North America at the present time [77], the synthetic production of resistant varieties provides a highly effective method of controlling plant diseases and increasing crop yields. The physiologic-race flora in any given region, however, varies somewhat from year to year and differs in its content as between one set of climatic conditions and another, and from one territorial region to another, so that in any new geographical area or individual country initial and repeated surveys of the prevailing physiologic races and the search for and discovery of suitable disease-resistant material are prerequisites to the establishment of a synthetic-breeding programme on a sound and satisfactory basis. Other factors essential to the success of this work are the development and application of techniques for the culture of the parasitic organism, for plant inoculations, and for the creation of artificial epiphytotics in the field nursery.

Tests of the resistance or susceptibility of the breeding material may be carried out with single-race cultures, or with a composite inoculum representative of the prevalent physiologic races in the locality. Where the reactions to a number of physiologic races are known to be inherited as a single group, the composite inoculum may be made up with single-race cultures representative of each separately inherited group. In the development of artificial rust epidemics in the field nursery the main aim is to produce a heavy infection so as to minimize the chances of any susceptible segregates escaping infection.

To secure a uniform distribution of the infection when breeding for resistance to the rusts in the field, 'spreader rows' of one or more susceptible host varieties are usually sown at frequent and regular intervals between the hybrid drills and lengthwise between the traverses. These rows are inoculated early in the season by making needle-injections of groups of plants at intervals along the spreader rows, using a water suspension of composite spores, or the composite inoculum may be applied as a dust with a 'puffer' equipment using dry spores diluted with talcum powder [106, 107, 103]. The latter operation is best carried out in the early morning or late evening when the dew is

on the foliage. Dusting of the spreader rows should begin early in the season so as to give about three multiplication generations of rust on the spreader rows and hybrid drills before observation notes are taken.

The breeding material may be subjected to infection either in the F_2 or the F_3 generation. Where the reaction to disease is inherited as a simple recessive, elimination of susceptible plants and plants heterozygous for susceptibility can be accomplished in the second generation of the cross, provided care is taken to develop a severe and uniform epiphytotic so that few or none of the susceptible plants escape infection. In most cases, however, resistance to infection by smuts and rusts behaves as a dominant character, and the inoculation treatments are therefore more usefully applied in F_3, when all families containing infected plants can be discarded and only the resistant ones continued for further study. When breeding for the simultaneous production of resistance to several kinds of parasitic fungi, large numbers of F_3 families should be grown so that the residual plants provide an adequate range of types for subsequent agronomic selection.

Testing for smut susceptibility is best carried out in a greenhouse in which the temperature and soil-moisture conditions during the early seed-germinating period can be kept under control [35, 34, 79]. Since dehulling of the grain is a laborious task, especially when large numbers have to be dealt with, a portion only of the F_2 seed may be used for the smut-inoculation tests and the remaining seed set aside for tests of resistance to stem and crown rust. The latter tests can then be separately made in pots in a greenhouse, or in short drills in the field. More satisfactory control is, however, obtained in the former. As an alternative to dusting the dehulled grain with smut spores, inoculation may be effected by immersion of the unhulled grain in a water suspension of spores under reduced air pressure, evacuating and releasing the air at successive intervals, so as to force the spores between hull and kernel.

Greenhouse infection with crown rust may be induced by damping the leaves of the young plants with a fine spray of tap-water, followed by dusting with a composite inoculum of uredospores diluted with talcum powder. After treatment the plants should be covered with a muslin tent, or placed in a large glass incubation chamber, for about 24 hrs. [108, 109, 107, 93]. All families showing positive reactions may be immediately eliminated. Inoculation of the residual plants for stem-rust infection may then be made by needle-injection of the stems with a water-suspension of composite spores, using a hypodermic syringe. At the end of the season final eliminations are made of plants susceptible to stem rust and of those families which have shown susceptibility to smut in the separate tests made for resistance to smut. In the following generation the selected material may be transferred to an isolated field nursery, when a repeated test on their resistance to rust may be made by the development of an artificial rust epidemic. Breeding and selection in subsequent generations then follow the procedure usual for handling hybrid-plant material. Before any new strains are multiplied with a view to marketing, check tests should be made to confirm their disease-resistant properties.

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HILL-LAND RECLAMATION IN MONTGOMERYSHIRE, WALES

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MONTGOMERYSHIRE, situated in mid-Wales, adjoining the English border, is a county of sharply defined hills and valleys, where, generally speaking, the valley-bottoms and the less steep slopes provide the arable crops and the best grazing, whilst the hill-tops are used almost entirely as rough grazings and sheep-walks. The stock-carrying capacity of the unimproved hill-tops is very low, rarely amounting to more than one sheep to one acre. Very little of this land shows signs of ever having been cultivated before; but Sir George Stapledon's work at Cahn Hill, near Aberystwyth, has shown that similar land could be made to grow better grass and to carry crops, provided it receives the proper treatment.

The War Agricultural Executive Committee therefore decided in June 1940, after the disaster of Dunkirk, to explore the possibilities of bringing certain of these areas into cultivation as part of the increased food-production drive. Although many problems were encountered the initial schemes were in the main highly successful, consequently the scope of the work was extended each year until 1945.

Problems.—Some of the problems encountered in relation to land reclamation in Montgomeryshire can be grouped under the following headings:

1. The initial ploughing and cultivations.
2. Soil amelioration and fertility restoration in terms of various crops: (*a*) potatoes; (*b*) sugar-beet; (*c*) pioneer crops consisting of brassica crops such as rape, turnips, or gramineous crops like rye and rye-grass; (*d*) grassland in terms of gramineous and leguminous components of the sward.
3. The microbiological aspects of virgin soils.
4. The results and the ultimate utilization of the improved productivity of such areas.

Areas involved.—These were situated in various parts of Montgomeryshire at elevations ranging from 800 to 1,600 ft. above sea-level with an average rainfall of 35 to 60 in., and amounted to a total area of nearly 7,000 acres.

Most of the land could be classified into four main groups according to the dominant type of vegetation. These were: (1) bracken, (2) nardus and nardus-fescue, (3) heather, (4) molinia.

Although the soil type associated with each kind of vegetation varied greatly, according to the results of soil analyses all the types had the following characteristics in common:

1. A marked degree of acidity with a pH varying from 3·8 to 4·4.

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2. A marked phosphate deficiency necessitating an initial dressing of 70 to 100 lb. of P_2O_5 per acre before cropping.
3. A relatively high organic-matter content which varied from about 12 per cent. in the bracken areas to as much as 60 per cent. in those dominated by heather.
4. A deficiency of potash, especially for potato-growing, on all except the bracken-covered areas.

Soils.—The soils underlying each of the vegetative types might be briefly described as follows:

1. On the bracken-covered areas there was a light loam soil overlying a naturally free-draining subsoil or shaley type of rock.
2. Under nardus and nardus-fescue was a heavier darker loam usually associated with a heavy clay subsoil, less naturally well-drained than the bracken-covered soils.
3. In the heather areas there was usually a high percentage of peaty organic matter mixed with and giving way to a heavy tenacious clay subsoil. Natural drainage was very poor.
4. The molinia areas, although usually at the lower elevations, were associated with a very heavy clay soil capped with a layer of peat and overlying an impervious clay subsoil.

None of the areas had ever previously been cultivated or for that matter fertilized within living or recorded memory. On the other hand, there was usually a good depth of soil free from stones and obstructions.

Initial cultivation.—Ploughing was normally carried out at a depth of at least 8–10 in. and in some places on the bracken areas at 12–14 in. No preliminary work or expense was necessary on any of the areas to clear scrub or trees or even to drain before ploughing could begin.

With high-powered tractors and ploughs capable of making a wide deep furrow no difficulties were encountered in the initial ploughing or cultivations. The one exception in this respect was found on the bracken areas, and then only when it was attempted to carry out deep cultivations and ridging operations for growing potatoes within a few months of ploughing. Under these conditions the bracken rhizomes fouled the cultivating and ridging implements. This difficulty could be largely overcome by ploughing 6 to 9 months before the spring in which the potato crop was to be planted, particularly if the land was devoted to growing some kind of pioneer crop to be eaten off by sheep or cattle. The treading and trampling of such stock quickened the rate of decomposition of the bracken rhizomes.

The best time to plough these areas was found to be July and early August when the bracken fronds were unfolding. Deep ploughing at this stage gave almost 100 per cent. kill of the bracken. Where such areas were ploughed before or after this period the bracken, although seriously reduced, was not by any means killed completely. It was found, however, when such land was directly reseeded that a very heavy rolling in the following year, when the surviving bracken fronds were unfolding,

would practically complete its destruction. Two further general points about the initial ploughing should be noted:

1. The chief aim in the initial ploughing should be to obtain maximum burial of the original vegetation. This is most important whatever the subsequent cropping, but especially in the case of direct reseeding, since reversion of the newly sown sward will be greatly increased by the survival of parts of the original herbage. For the same reason the cultivations after the first ploughing should be done carefully to leave the original herbage buried even when arable crops such as potatoes are being grown.
2. On the wetter areas, particularly where heather or molinia was dominant, the ploughing should be done in such a way as to maximize natural drainage by means of the ploughed furrow. On these areas wetness is a very real problem whatever the subsequent cropping, even reseeding.

These were the chief points concerning the initial cultivation of these areas. The basic problem, however, was that of rectifying the major deficiencies of such soils coupled with what might be called their general amelioration. This can probably best be illustrated by describing the experiences and difficulties encountered with a number of crops. It is always easy to be wise after the event, and it is therefore well to remember that most of these problems arose partly from a shortage of supplies of lime, phosphates, and potash, coupled with suitable personnel and machinery, as well as the great need and urgency to bring such areas into production as quickly as possible. The result, not confined to this work, was frequently a case of more haste less speed.

Potatoes.—The first interesting problem was encountered in growing potatoes on part of a reclaimed bracken area which, although it was known to have a pH of about 4, could not be limed at that time. Part of this area was given a dressing of a complete fertilizer containing ammonium phosphate approximately equivalent to 78 lb. N, 78 lb. P_2O_5, and 56 lb. K_2O per acre. Here the potato crop was almost a complete failure. The plants, in addition to being slow to start growth, were pale green as well as small, poor, and stunted throughout the season. On a windy sunny day the leaves curled up and gave the crop the appearance of being heavily infested with leaf-roll. Furthermore, the parent tubers mostly remained firm and hard; some of them when dug up and replanted in lowland soils produced normal healthy plants and the parent tuber decomposed in the ordinary way. Wallace and Hewitt [1] have investigated the phenomenon and concluded that it is entirely due to the effects of a deficiency of calcium.

On an adjoining unlimed area which received a similar dressing of nitrogen, phosphate, and potash per acre in the form of basic slag, sulphate of ammonia, and muriate of potash, a normal, healthy, vigorous crop was produced. This provided the key to the solution of this problem. More precise and definite information was obtained in the Agricultural Chemistry Department, Aberystwyth, where analyses were made of the leaves and stems of plants growing in these and other plots

with and without lime but a sufficiency of nitrogen, potash, and phosphate, the last-named being in both the calcic and non-calcic forms. The results of this work by Davies, Fagan, and John have been published [2] and might be summarized briefly as follows: The leaves and stems of the potato haulms grown on the unlimed or unslagged areas were exceptionally low in both calcium and phosphoric acid. On the areas that had received about 30 cwt. of ground limestone there was a fourfold increase in the calcium-content of the stem and leaves; this was also associated with a marked increase in their content of phosphoric acid. The influence of various manurial treatments was investigated over a period of two years. If the yield from the unlimed plots is put at 100, which is approximately equal to a total yield of one ton per acre, then the results of various treatments are as follows:

	Yield
1. 5 cwt. complete fertilizers (14% N, 14% P_2O_5, 10% K_2O), no lime	100
2. 5 cwt. complete fertilizers, 30 cwt. ground limestone	1,000
3. 30 cwt. ground limestone only	500
4. 3·3 cwt. sulphate of ammonia, 4·6 cwt. 15% basic slag, 1 cwt. 50% muriate of potash equivalent to (1)	1,100
5. 3·3 cwt. sulphate of ammonia, 4 cwt. 18% superphosphate, 1 cwt. 50% muriate of potash equivalent to (1)	650

It is clear from these results and the critical chemical analyses of the haulms that the basic limiting factor was calcium acting in a dual capacity: on the one hand, as a plant-food, and on the other, as an essential base to render the phosphate into a condition available to the plant. In its absence a phosphate deficiency as well as a calcium deficiency occurred. Similar results were found on areas that were originally dominated by nardus, nardus-fescue, and heather. Full details have been published elsewhere [3].

On the more peaty areas that were limed and given a complete fertilizer it was found that the tubers did not keep so well during the winter as those grown on bracken soils. Analyses of such tubers showed them to be low in dry-matter and high in nitrogen.

Sugar-beet.—Experiments were carried out on a limited scale with sugar-beet on the drier bracken and fescue areas. It was not possible to grow this crop successfully during the first three years. Although on the limed areas plants grew well until after singling, subsequent growth was slow and stunted. When lifted the roots frequently showed excessive fanging, presumably due to acid conditions still prevailing in the lower parts of the soil even two or three years after liming. Where very heavy dressings of lime were given boron deficiency occurred in the crop. It appears that for such a crop as sugar-beet a fairly long period of soil amelioration is necessary before it can be grown successfully.

Pioneer crops.—As the reclamation work progressed a system of pioneer cropping was introduced, i.e. the crops were usually grown on the land relatively soon after it was ploughed, limed, and manured. Certain interesting results were obtained. Even when the recommended quantities of lime were applied together with nitrogen, phosphate, and potash, pioneer brassica crops such as rape, turnips, and kale frequently

either failed entirely or made only poor growth. This was particularly true when there was only a short period between ploughing, liming, manuring, and the sowing of the crop. On the other hand, rye, Italian ryegrass, and perennial ryegrass gave satisfactory results under such conditions.

One experience of the behaviour of sheep grazing a pioneer crop of Italian ryegrass, rape, and turnips, is worth mentioning. On one area of about 50 acres, all of which was given a dressing of about 2 tons of ground limestone per acre, approximately one-half was then given 2 cwt. per acre of a compound fertilizer (18 per cent. N, 18 per cent. P_2O_5) equivalent to about 40 lb. N, 40 lb. P_2O_5, whilst the other half was given an approximately similar dressing of a mixture of sulphate of ammonia and basic slag. The sheep when turned in to graze the crop eventually settled down on to the part which had been given basic slag and grazed it relatively bare before grazing the other part. Some factor had presumably favourably influenced the palatability of the mixture grown on the land that had received a dressing of basic slag.

Reseeding.—Certain areas, which on account of their situation, tractability, or some other reason were not suitable for growing arable crops, were reclaimed in order to turn them into more productive grassland. In a few cases the land was cropped with pioneer crops of mixtures of Italian ryegrass and/or rye and rape and turnips prior to being reseeded. In the main, however, a policy of direct reseeding was adopted, using short-term leys made up of commercial strains of ryegrass, timothy, or cocksfoot, according to the type of soil.

Some seeds-mixtures consisted solely of pedigree strains of grasses and others of half-commercial and half-pedigree strains. These types, although used on several hundreds of acres, were in the minority. Legumes such as red clover and alsike were included in most of the seeds-mixtures, and some kind of white clover was common to nearly all the mixtures.

As might be gathered from the experiences given above with pioneer crops, there was no difficulty in establishing any of the species or strains of grasses, provided proper cultivations and methods of sowing were carried out and the land properly limed and manured. The same cannot, however, be said of the legumes.

Establishment of clovers.—It was found that the various clovers could be arranged in approximately the following order in relation to their ability to establish themselves and grow reasonably well in such newly formed swards: white clover, alsike, late flowering red clover, broad red clover.

Both alsike and any kind of white clover were more easily established than either of the red clovers, especially broad red clover. Almost invariably the establishment of any of these legumes was much easier and more successful on areas that had borne previously a pioneer crop. So far as can be judged, the behaviour of the legumes on land reseeded without a pioneer crop was determined by a combination of factors such as soil acidity, available calcium, and available phosphate. What happened to the red clovers was that the seed germinated and seedlings

became established, but after about 8 to 12 weeks from the date of sowing they began to turn yellow and then died off fairly quickly.

The presence or absence of the appropriate strain of symbiotic bacteria is also a factor to be considered. Although it was not possible to carry out any detailed experiments on this point, one fairly large-scale trial was done with white clover, using inoculated against non-inoculated seed. Subsequent analyses showed that during the first year there was almost 100 per cent. better establishment of white clover on the area where inoculated seed was sown. By the summer of the second year there was very little difference between the two areas in terms of the percentage ground covered by white clover.

This question of strains of soil bacteria leads to the wider issue of microbiological activity in virgin soils of these types, a subject about which little is known. Interesting work bearing on this problem has been carried out in France. According to a report by F. C. Gerretsen, which is mentioned in a recent article by Hanley [4], soil micro-organisms increased the uptake of phosphate by the roots of plants in their immediate neighbourhood. The question might be asked: is the value of pioneer cropping simply one of soil amelioration in terms of aeration, weathering, liming, and fertilizing coupled with the manurial value of animal droppings? Or is there some particular microbiological value in the animal excreta? If this is so, how far can the animal excreta be replaced by the use of extra amounts of nitrogenous fertilizers? This was a field into which we did not enter, but there was some evidence that in many cases heavier dressings of artificial nitrogen would have been both beneficial and economic.

Fertility following reclamation.—The cropping potentialities of these reclaimed areas is appreciable especially where they are dominated by bracken or nardus or nardus-fescue, once soil amelioration in its widest sense has been achieved. On such land it has frequently been possible to grow 6 to 9 tons of ware potatoes or a similar yield of good-quality seed potatoes. In the drier summers good yields of corn have been obtained, the best varying from 25 to 30 cwt. for wheat, oats, and barley. Cereal-growing is not, however, to be advocated as a general system of cropping in areas of this kind. From a national point of view the best results have no doubt been obtained through reseeding and improving the productivity of such soils in terms of grass production. Over a period of seven years it has been found that these new swards, in addition to carrying a better class of stock, have an average increased stock-carrying capacity of at least half a beast per acre over and above the stock which they previously carried, or in terms of live weight an increase of about 125 lb. per acre. This increased productivity has, however, created a wider and apparently a more difficult problem, namely, that of utilizing the increased stock-carrying capacity in terms of animal production. From the national point of view it would be most unfortunate if these reclaimed areas were allowed to revert to their original condition.

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BREEDING FOR DISEASE-RESISTANCE IN CANADA

PART II. FLAX AND FORAGE CROPS

C. H. GOULDEN AND T. M. STEVENSON *et al.*[1]

WITH PLATES 9, 10

Flax.—THE flax plant is not a native of North America but was introduced from Europe, and with it have come most of the principal diseases which now attack it here. For some time flax in this country was a relatively minor crop occupying a very small acreage in comparison with cereals, and injury from diseases was moderate as compared with that to other crops. Also flax has been grown more frequently on new land than were the cereals and the comparative freedom of new breaking from disease organisms may have kept the losses from diseases relatively low. However, with a large increase in acreage taking place during the war years there has been a revival of active interest in the diseases of flax.

The important diseases of flax in Canada at the present time are wilt, *Fusarium oxysporum f. lini* (Bolley) Snyder and Hansen, rust, *Melampsora lini* (Pers.) Lev., and pasmo, *Septoria linicola* (*Speg.*) *Gar.* (*Sphaerella linorum Wr.*). Two other diseases, more limited in distribution, are anthracnose, *Colletotrichum linicola* Pethyh. and Laff., and browning and stem-break, *Polyspora lini*, Laff.

Until 1942 flax wilt was the only important disease affecting this crop in Canada. The varieties Premost, Crown, Diadem, and Novelty used for many years after the commencement of flax-growing were all susceptible to this disease, but as the area under flax was small, farmers were able to rotate their crops and therefore avoid loss. In the meantime, Dr. H. L. Bolley in the U.S.A. had indicated the cause of flax wilt and how selection on wilt-infested soil could be used to isolate varieties with resistance. The varieties Bison and Redwing that resulted from this breeding programme were found to be widely adapted in Canada and by 1940 the acreage of flax consisted almost entirely of these two varieties.

A flax-wilt nursery on which flax tests have been conducted for the past 25 years has been maintained at the Central Experimental Farm at Ottawa. The results show that Bison has higher resistance to flax wilt than Redwing. However, since the earlier maturity and high quality of the seed of the latter variety are characteristics desired in Canadian flax, both have been used in our breeding programmes. Considerable variations in the flax-wilt organism have been found both in the U.S.A. and Canada. To overcome the effect of this variation in the breeding work a second nursery was established at Ottawa and another at the Dominion Experimental Farm at Indian Head, Saskatchewan. Soil from the wilt nursery at the University of Saskatchewan, Saskatoon, is also used at Ottawa in pots in a constant-temperature tank, similar to the one used by Millikin [1].

Rust of flax appears in Canada wherever flax is grown. Severe infesta-

[1] The collaborators are given in Part I, p. 133.

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tions are usually confined to localized areas where temperature and moisture conditions are favourable and in crops located near sources of local infection. In 1942, however, a heavy rust-infection was general in western Canada and adjoining areas in the U.S.A. Losses were particularly heavy, since the Bison variety occupying about 75 per cent. of the area in flax is extremely susceptible to the forms of rust that were prevalent in this epidemic. This situation was temporarily relieved by the use of the variety Royal, which is moderately resistant to flax rust. It was distributed by the University of Saskatchewan in 1940. By 1947, Royal had almost completely replaced Bison in Saskatchewan and Manitoba, although in Alberta, where rust is not so prevalent, Bison still occupies about a third of the acreage of this crop.

Environmental conditions in the plant-breeding nursery at Ottawa are such that artificial epidemics of rust are often difficult to establish, therefore many of the new strains are tested in co-operation with the Laboratory of Plant Pathology at Winnipeg, where field tests are carried out. At Ottawa most of the work is carried on in the greenhouse during the autumn and winter season. Rust-resistant parents used included Walsh, 8c, and other lines from the Argentine along with Ottawa 770B. The latter is a selection made by Sir Charles Saunders from the cross La Plata A × Yellow Seed C. It has been used extensively in breeding for rust-resistance as it carries immunity to all the forms of flax rust known in North America.

As a result of this breeding programme the variety Rocket from the cross Argentine 8c × Redwing was produced and distributed in the spring of 1947. At the same time the variety Dakota, from the cross Bison × Renew selected by the United States Department of Agriculture, and Sheyenne, an early maturing variety, selected from the cross Nuda × Ottawa 770B by the North Dakota Experiment Station, were licensed for sale in Canada. With these new varieties, the situation should be well in hand for the time being. However, these varieties are not entirely satisfactory from other standpoints, and therefore breeding work is being continued intensively with a view to the production of more satisfactory rust-resistant varieties.

Pasmo was first reported from western Canada in Manitoba in 1940, although it was found throughout the flax nursery at Ottawa in 1939. Flax-disease surveys made at the end of August in 1945 and succeeding years show that it has increased in range and severity each year, appearing in Saskatchewan for the first time in 1946.

Field inoculations made at the Laboratory of Plant Pathology at Winnipeg on a wide range of varieties and selections show that varieties differ in their tolerance to the disease but no marked resistance exists. Crystal, C.I. 1116, and C.I. 1153 are more tolerant than other varieties tested.

The flax-breeding project at the present time includes the use of backcrosses to such parents as C.I. 1116 and C.I. 1153, which have resistance to flax rust, wilt, and as much tolerance to pasmo as has been available in the material tested. Field nurseries for flax wilt and pasmo have been very successful in screening out susceptible material.

The greenhouse has been found useful in handling populations for

flax-rust epidemics and flax wilt also. After these populations have been screened for disease they are selected for agronomic characters either in the Cereal Division or on Experimental Farms. Material from preliminary trials is tested for oil-content and iodine-number. The object is to obtain varieties with a large yield of seed of high quality and free from disease. Although consideration is given to the yield and fibre-quality of straw in our linseed varieties, no attempt has been made to select for this character.

Forage crops.—The importance of plant-disease as a factor in reducing forage-crop yields in many parts of Canada has but recently been fully recognized. In consequence, breeding for disease-resistance in certain crops is now, for the first time, receiving the attention that it deserves. Whereas good cultural methods, seed-disinfection, and well-planned rotations can do much to alleviate disease, in many cases the development of resistant strains appears to be the only permanent solution. Many of the diseases which attack forage species, though troublesome and causing varying seasonal losses, have never attained epidemic proportions, but losses from some other diseases have been so heavy that it has been necessary to initiate extensive breeding programmes, the results of which will, in some regions, determine whether or not the continued production of these crops will be possible.

A few destructive diseases occur chiefly in limited areas where certain crops are grown extensively. Some diseases of the soya-bean crop are a good example. In Canada this crop is concentrated mainly in SW. Ontario, with smaller acreages in other parts of Ontario, Manitoba, and Alberta. According to Hildebrand and Koch [2], 13 or approximately one-half of the known parasitic diseases of the bean have been found to occur in SW. Ontario. On the other hand, only 8 of these diseases have been reported elsewhere in the Dominion, and these were mostly of the trace-infection type. Of the various diseases, that of bud blight, caused by a tobacco ring-spot virus, is, according to Hildebrand and Koch [3], potentially dangerous and losses are already appreciable. Whilst growers can at present grow soya-beans profitably, using the standard varieties, it is apparent that the time will come when these standard varieties must be replaced by new disease-resistant strains.

Although much attention is now centred on major disease problems and the means to overcome them, we must not overlook the fact that the plant-breeder has always selected only the vigorous, healthy plants, taking full advantage of natural disease epidemics to eliminate susceptible material. By growing an array of cloned and selfed lines, and comparing their reaction, demonstrable differences are often striking. By combining the more resistant lines, new strains superior to commercial varieties have been developed; for example, Climax Timothy, recently produced by the Division of Forage Plants, Central Experimental Farm, Ottawa, is comparatively free from the common leaf diseases. Such leaf diseases as timothy rust have been shown by Bird [4] and others to weaken the plants and thus permit considerable winter-killing.

Diseases in legumes.—At present the most serious diseases in forage crops in Canada appear to be among the legumes, especially alfalfa

(lucerne) and red clover. Besides the more destructive alfalfa diseases described later, the crop is subject to attack from numerous other diseases which, although of minor importance regionally and seasonally, have a pronounced aggregate effect. Virus diseases, of which Witches' Broom is typical, is more commonly found in fields in British Columbia than in other provinces. Leaf-spot diseases, of which *Pseudopeziza medicaginis* (Lib.) Sacc., is the most common pathogen, have a general distribution and cause variable losses. Root rot, caused by *Sclerotinia* spp., produces minor losses by causing thinned-out stands in eastern Canada. However, alfalfa is more resistant to this pathogen than red clover. Mildew and leaf rust are limited mainly to trace infections in certain seasons.

In red clover, virus diseases are also fairly common, but in eastern Canada the major disease appears to be *Sclerotinia trifoliorum* Eriks., and in consequence, a breeding programme to obtain strains of clover resistant to this disease is being emphasized. Powdery mildew, *Erysiphe polygoni* DC., is present on the red-clover aftermath in most seasons, but many plants show resistance to it. Considerable concern has recently been aroused among the growers of single-cut red clover in Alberta, by a recent outbreak of Northern Anthracnose, caused by *Kabatiella cantivora* (Kirch.) Karak. The attack appears to be centred in the Lacombe area in Alberta and an active breeding-project to develop resistant strains has been started at the Dominion Experimental Station located at that point. A world-wide collection of strains and varieties is now under test, with a view to finding resistant breeding material.

On the plant-breeding projects detailed below, the Division of Botany and Pathology has assigned pathologists to work with the plant-breeder. This enables the research team to carry out artificial inoculations with the pathogen, and not depend entirely on natural epidemics. It is also possible to make more reliable field surveys which serve to underline the urgency of the project. Field nurseries are located at the regional experimental stations nearest the focal points of disease, and selections must thus survive the double gamut of greenhouse and field infection. Tests conducted on the widely dispersed branch farms and stations of the Dominion Experimental Farms Service will provide an opportunity to appraise finally the resistant strains, and aid in determining their general regional adaptation.

Breeding alfalfa for resistance to bacterial wilt.—Bacterial wilt (*Corynebacterium insidiosum* (McCall) G. J. Jens.), which has been a troublesome disease in the U.S.A. for the last 25 years, was first noted in Canada in 1939. The focus of infection was in the irrigated lands of southern Alberta. By 1943 it was found on non-irrigated land east of Edmonton, in about one-quarter of the fields examined. Since then the disease has been found in Saskatchewan and Manitoba, and special concern is felt in the northern sections of the prairie provinces where large areas are devoted to alfalfa-seed production. In Ontario, which contains one-half the country's alfalfa acreage, wilt has only recently been observed, and it is probably only a matter of time before it becomes a problem in that province.

On the irrigated areas of southern Alberta it has been observed that although disease development is slow in the first and second years after crop establishment, by the third year the stands show pronounced thinning out, and it is often not profitable to maintain the field in alfalfa the fourth year. Although certain cultural practices may delay the development of wilt, the only effective measure of control appears to be the use of resistant varieties. Unfortunately, the widely grown variety, Grimm, is almost completely susceptible. Cossack, Viking, and Ladak have variable degrees of resistance which might prolong the life of a stand for a year. Plant-breeders in the U.S.A. have developed two highly resistant varieties, Ranger and Buffalo, but these lack dependable winter hardiness under Canadian conditions, particularly in the prairie provinces. Consequently, in the breeding programme it is necessary to screen out the hardier components of wilt-resistant stock. At the same time, the selections must be at least equal to Grimm in yield of forage and seed, and if possible carry resistance to crown-rot and blackstem diseases.

The procedure followed is to maintain nurseries at the Lethbridge Experimental Station, where the breeding work is under the immediate supervision of Mr. R. W. Peake. Dr. M. W. Cormack, Pathologist, Dominion Laboratory of Plant Pathology, Lethbridge, co-operates in maintaining inoculation for seedling work, assisting in rating the degree of infection, and in making disease surveys. The staff of the Dominion Forage Crops Laboratory, Saskatoon, Sask., co-operates in all of the forage-plant breeding projects in western Canada in an advisory capacity, as well as by conducting actual breeding work.

The present organization on this project was made in 1945, and good progress has been made in the past 4 years. In 1946 the bacterial wilt nursery contained 99 clonal lines from the Dominion Forage Crops Laboratory, Saskatoon, of which 8 later proved to have wilt resistance; 52 lines from the University of Wisconsin, of which 25 proved resistant; 75 lines from Lethbridge, of which 21 were found resistant to wilt. These surviving selections were then cloned in 1947 and set out in tests to measure such characters as combining ability and seeding capacity. In 1947 and 1948 several hundred clonal rows selected for such characters as resistance to blackstem, resistance to crown rot, high seeding capacity, rhizome development, and good survival in old fields, have been established in the wilt nursery and are undergoing test. The men actively engaged in this project are confident that it is only a matter of time until wilt-resistant strains suitable for a variety of purposes, and adapted to a range of soil types and climates, will be made available for Canadian production (Figs. 1, 2, 3, Plate 9).

Breeding alfalfa for resistance to winter crown rot.—The unnamed, low-temperature Basidiomycete responsible for this disease was isolated first in 1931, according to Broadfoot [5], and later was described by Broadfoot and Cormack [6]. Damage occurs early in the spring at freezing temperatures when the alfalfa plant is dormant. The fungus is very virulent under those conditions, and attacks many other legumes and grasses, as well as alfalfa. According to Cormack [7], damage varies greatly from year to year. In northern Saskatchewan in 1942, and northern Alberta

in 1943, when epidemic conditions prevailed, many alfalfa stands were very heavily damaged. The disease occurs throughout the prairie provinces, but is most destructive in the northern sections.

Selection for resistance to this winter crown-rot disease was started in 1941. Varieties of *Medicago falcata* L. and the Cossack and Viking varieties have proved to be the best sources of parent material. Between 200 and 300 plants, which are more or less resistant to the disease, have now been found. A large number of selfings and inter-crossings have been made at the Dominion Forage Crops Laboratory, Saskatoon, Sask., with these plants, and the progenies tested in a nursery at the Dominion Laboratory of Plant Pathology, Edmonton, Alta. Results are encouraging, as there is a definite concentration of resistance evident in the progenies. Resistant plants have been out-crossed to plants selected for wilt-resistance, high seed-yields, &c., and resistance has been found in progenies of these crosses also. The object of the breeding programme is to build up a large enough population of resistant plants which are also desirable in other characteristics, so that enough parents with high combining ability can be selected for the synthesis of hybrids or varieties suitable for commercial production in western Canada.

Breeding alfalfa for resistance to blackstem.—A recent article by Cormack [8] on the blackstem disease of alfalfa, as caused by *Ascochyta imperfecta* Peck., contains a good description of the distribution and symptoms of the disease. It is primarily a parasite of *Medicago sativa* L. but occurs also on other cultivated and native legumes. The first record was from New York in 1908, but it is now known in Great Britain and throughout Canada and the U.S.A. Seed-production fields in Saskatchewan are seldom free of blackstem and usually stands are heavily damaged by defoliation and stem lesions. The organism occurs also in root lesions and may cause damage to pre-emerged seedlings.

In 1946 selection for resistance was begun at the Dominion Forage Crops Laboratory at Saskatoon, Saskatchewan. No immunity was found, but about 20 plants showed some resistance. The Cossack variety appeared more promising as a source for selection than the Grimm, Ladak, Turkestan, or Viking varieties. Additional selections were made in 1948. The 1946 selections have been selfed and intercrossed and the progenies set out in a disease nursery at Saskatoon. In 1948 the season was too hot and dry to obtain good infection. As soon as satisfactory ratings are secured, desirable progeny plants will be selfed, intercrossed, and also back-crossed to the best parent clones. The objective of this breeding programme is to concentrate the genetic factors for resistance so that desirable plants can later be combined in a synthetic variety or commercial hybrid.

Breeding for resistance to crown rot in red clover.—Crown rot (*Sclerotinia trifoliorum* Eriks.) has proved a troublesome disease for the past 25 years in breeding work with double-cut red clover at Ottawa. Epidemics are usually most severe in cold, wet springs on land which has had red clover frequently in the rotation. Whilst it is impossible to make a close estimate of the losses suffered in farmers' fields in eastern Canada, there is reason to believe that these losses are severe in some seasons, and in

many cases losses attributed to winter-killing are known to be due to attacks of this disease. This fact was borne out in 1947 in a study of nursery material at the Division of Forage Plants, Central Experimental Farm, Ottawa. The winter survival averaged 88 per cent., but the yearly survival averaged 46 per cent. Many plants made a few days active growth in the early spring, and then died. An examination of these plants and of the 12 per cent. that were formerly classified as winter-killed showed the typical Sclerotinia in the crowns; so-called winter-killing in this case was definitely due to the disease rather than to a lack of winter hardiness.

The double-cut variety 'Ottawa' produced by the Division of Forage Plants has considerable resistance to crown rot due to the selection of healthy surviving plants over a period of years in infected fields. The yearly survival of the variety 'Ottawa' in 1947 was 15 per cent. higher than the next most resistant variety in the test (Totin from Norway). Nevertheless, it is known that by following a programme of seedling inoculation under controlled conditions speedier results can be achieved. Consequently, work was begun along these lines in the spring of 1948.

Several thousands of seedlings of the 'Ottawa' variety were grown in trays of soil heavily inoculated with the pathogen. Moisture and temperature for the first two weeks were kept optimum for the pathogen. The surviving plants were then set out in a field nursery. The better plants that survive two winters will be crossed and their seedling progenies re-tested. After several cycles of this treatment it is hoped greatly to improve the resistance of red clover to this disease (Figs. 4, 5, Plate 10).

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FIG. 1. Wilt-infested, six-year old plot of Grimm in the foreground, showing thinned stand and weed invasion; Ladak in background, showing normal stand and freedom from weeds

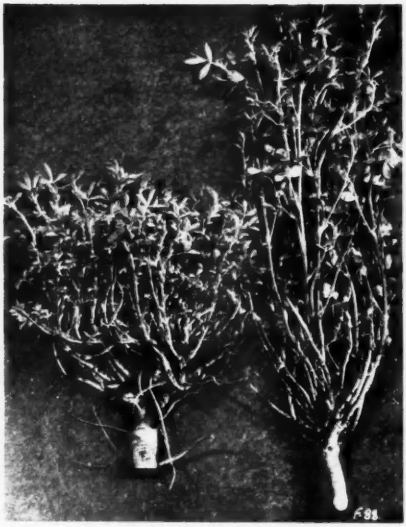

FIG. 2. Wilt-infested alfalfa plant at left, and healthy plant at right

FIG. 3. Cross-section of wilt-infected alfalfa root to left, and healthy root to right

FIG. 4. Red clover breeding nursery—lines showing only very slight injury from Sclerotinia

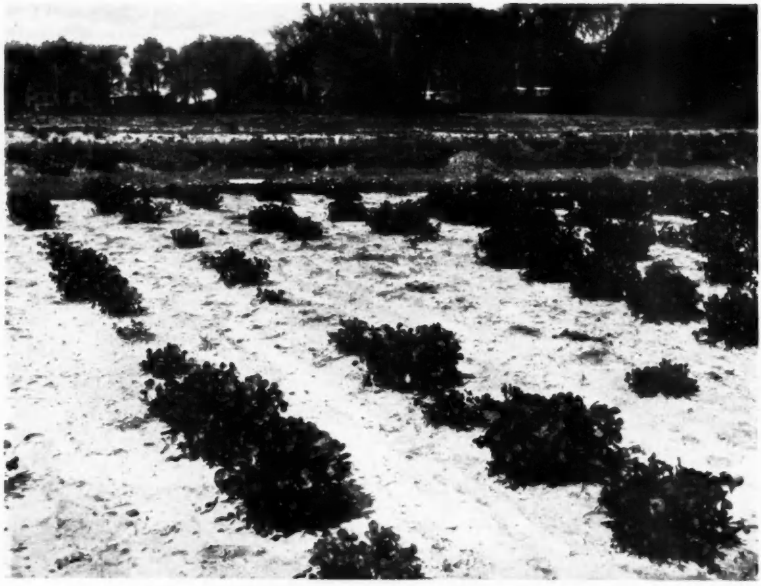

FIG. 5. Red clover breeding nursery—susceptible lines showing severe injury from Sclerotinia

DAIRY HERD FERTILITY

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General considerations.—Improvement in the control of abortion and mastitis in the last decade has emphasized the great economic importance of the persistent problem, common to most dairy herds, of failure to breed regularly. The matter received much attention before the war when studies were made in several countries of the 'wastage' of dairy cows, that is, of the extent and causes of disposal of cows from dairy herds; and in nearly all of these investigations 'sterility' was given as the most important cause of disposal. A critical study of the treatment of individual cows, however, would probably have shown that in many cases the animal had been left barren without much effort to achieve successful conception other than by one or two repeat services. In addition to these statistical studies there has, of course, been extensive investigation of the physiology and pathology of individual cows that fail to breed. Rarely, however, has the fertility of a herd received much attention although this is, in fact, the unit with which the dairy farmer is primarily concerned. There are obvious reasons for this. In most commercial herds detailed service records over a period of years are not available. If they are available, the culling policy will often be so stringent that the true fertility of the herd is not apparent.

This communication is concerned with the herd belonging to the National Institute for Research in Dairying where records are in sufficient detail to warrant analysis, and where culling because of failure to breed usually takes place only after persistent effort to achieve conception. The service records for this herd over the last decade are of added interest in that the period includes the change from natural to artificial mating and the introduction of vaccination against abortion. Also the breeding problems have, for most of the period, been under routine veterinary control.

We have considered it wise to avoid the term 'sterility' since the completely sterile cow or heifer seems, from our data, to be rare. We have attempted to assess the importance of the problem by the degree to which the cows and bulls in the herd depart from perfect fertility. Unfortunately, there are many ways of stating this. No one standard will give anything approaching a complete measure of herd fertility and there is no general agreement as to which standards give the most useful information. Thus, one investigator will quote the number of calves per 100 cows per annum; another will quote the number of services per conception; another will give the percentage of cows conceiving to first service or subsequent services; another will give the percentage of all services resulting in conception; yet another will assess the problem by the proportion of cows sold because they failed finally to be served effectively. There are, however, two methods of summarizing service-record data commonly used.

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The first is to take the cow as the unit and study the total numbers conceiving and the numbers conceiving at first, second, third, &c., service. The other method is to take the mating as the unit irrespective of cow and to study the proportion of effective matings in particular circumstances. The latter method is useful where large numbers are concerned, but in smaller numbers the effect of one infertile cow which may be served many times may lead to false conclusions. It must be borne in mind that the first method needs careful application since conception rates based on it may reflect not only inherent fertility in the cows and bulls but also culling policy.

The N.I.R.D. herd.—The herd, which from its inception has been replaced entirely by home-bred female stock, consists of about 50 pedigree and grading-up Shorthorn and 10 pedigree Guernsey cows and their followers numbering an average of about 70 or 80 head. Although nearly all stock at some time during their life in the herd are on experiment, most of those under consideration have not been subject to drastic treatment likely to have much effect on their breeding efficiency. The results discussed below may therefore be considered as typical of a self-contained herd in the south of England.

After 10 years of freedom from contagious abortion there was a severe outbreak in the herd in 1933. A policy of segregation of reactors to the agglutination test was adopted, and by 1939 no reactors appeared in the negative section of the herd. The disease reappeared in 1940 but by 1942 it had apparently been eliminated from the herd. A policy of vaccination with S. 19 of all stock over 6 months old was started in August 1944. This survey of herd fertility, therefore, follows a period when abortion was a major problem, but by 1937 a fair measure of control over the outbreak had been obtained, and there is no reason to believe that the attack had much influence on the fertility of the herd between 1937 and 1947, the period with which we are concerned.

It must also be recorded that from 1937 to 1942 all animals were served naturally, but early in 1943 the first artificial matings were carried out, and thereafter natural mating was progressively diminished each year until 1947 when practically all matings were artificial. Two bulls were used in the last year of natural mating, one 10 years old and the other 4 years, and these two animals were also used for artificial insemination during the first year of this method of mating.

Generally, the aim has been to calve each cow at approximately 12 months after her last calf. Most of the heifers have been calved into the herd in the autumn in order to obtain maximum production in the high-price winter months. For one reason or another most cows calved a little later each year. Nevertheless, the 365-day interval may be used as a convenient, if somewhat idealistic, objective; in the data given below an effort has been made to indicate the extent and manner in which we have fallen short of it.

Conception rate.—In Table 1 an attempt has been made to illustrate numerically not only the overall conception rate and the conception rate for first and subsequent services, but also the effect of service and culling policy. The data are classified by years and by calving groups. It is first

TABLE 1. *Number of Cows served and Number conceiving (a) For each year all ages combined; (b) For each age-group all years combined*

Year	Total no. cows and heifers at or reaching service-able age	No. animals listed for service during the year	No. having 1st service during the year	No. and per cent. eventually conceiving		Percentage conceiving after					Percentage not conceiving after		
				No.	per cent.	1st service per cent.	2nd service per cent.	3rd service per cent.	4th service per cent.	5th or later service per cent.	1st service per cent.	2nd service per cent.	3rd or later service per cent.
A. *For each year—all ages*													
1937–8	81	56	56	50	89·3	46·4	25·0	10·7	5·4	1·8	3·6	..	7·1
1938–9	91	55	54	47	87·0	38·8	18·5	16·7	11·1	1·9	3·7	1·9	7·4
1939–40	79	58	57	47	82·4	56·2	14·0	7·0	3·5	1·8	3·5	3·5	10·5
1940–1	80	55	55	48	87·4	54·6	16·4	9·1	5·4	1·8	7·3	..	5·4
1941–2	83	70	70	65	92·9	51·4	14·3	12·9	11·4	2·9	1·4	..	5·7
1942–3	73	56	55	51	92·9	54·6	29·1	5·5	3·6	..	1·8	1·8	3·6
1943–4	79	66	66	55	83·4	43·9	15·2	4·5	7·6	12·1	1·6	4·5	10·6
1944–5	82	67	66	52	78·9	56·0	12·1	7·6	3·0	..	9·1	6·1	6·1
1945–6	84	74	74	66	89·3	63·5	13·5	6·7	4·0	1·4	1·4	2·8	6·7
1946–7	81	74	74	71	95·9	64·9	14·9	10·8	4·0	1·4	1·4	..	2·6
Total (No.)	813	631	627	552	..	336	106	57	37	16	21	13	41
Total (per cent.)	..	..	..	..	88·0	53·6	16·9	9·1	5·9	2·6	3·3	2·1	6·5
Age-group						B. *For each age-group—all years*							
Maiden heifers			196	161	82·1	45·9	18·4	9·2	6·6	2·0	3·6	4·1	10·2
1st calf			114	98	86·0	49·1	15·8	8·8	9·6	2·6	5·3	1·8	7·0
2nd calf			111	102	91·9	57·7	16·2	11·7	3·6	2·7	2·7	..	5·4
3rd calf			83	78	94·0	59·0	18·1	7·2	7·2	2·4	1·2	2·4	2·4
4th calf			57	51	89·5	68·4	12·3	3·5	1·8	3·5	7·0	..	3·5
5th or later calf			66	62	93·9	57·6	18·2	12·1	3·0	3·0	..	1·5	4·5
Total			627	552	88·0	53·6	16·9	9·1	5·9	2·6	3·3	2·1	6·5

worth noting that in the 10 years an average of 18 animals per annum were never served. The great majority of these were animals which were, for one reason or another, culled or listed for culling, although a few were animals where service was withheld for a time to allow the animal to pick up in condition or to convert a late spring calver to an early autumn calver. Another point is the very small proportion of cows listed for service which were not, in fact, served. In 10 years only 4 animals fell into this category. This was partly due to the successful treatment of the small number of animals that failed to come on heat (see Table 3), and in part it reflects the keen observation of the herdsmen concerned. In general this type of infertility has been of comparatively little importance.

On the basis of the total cows served at least once throughout the 10 years, 88 per cent. eventually conceived. There is variation from year to year in this conception rate from a minimum of 78·9 per cent. to a maximum of 95·9 per cent. These data must, however, be considered in relation to the extent of the efforts to serve those which did not conceive. Thus, for example, in 1944–5, when the rate was lowest, 9·1 per cent. of the cows were culled with only one service and 6·1 per cent. with only two. Most of these animals were found to be non-pregnant at a late stage in lactation when, in practice, it was uneconomic to serve them again, yet it is reasonable to suppose that at least some of these animals would have conceived to later services.

On average, only a little over half of the cows that were served held to the first service. On the other hand, the data indicate that there is a good case for a third or even a fourth service. Ignoring 442 animals which held to the first and second service and 34 that were culled after only one or two services, 151 were served 3 or more times and of these no less than 110 were eventually got in calf, 94 of these with only one or two further services. After a fourth ineffective service the likelihood of pregnancy becomes rather remote.

In the calving groups there is a marked rise in percentage conception as the age increases from maiden heifers to 3rd-calf cows. There is a drop in the rate for the 4th-calf cows, but this is probably fortuitous since in this group an abnormal proportion of animals were discarded after only one service, and here again persistent service may have raised the rate to that of the other older cow-groups. The lower conception rate in heifers and younger cow-groups has been noted in other studies [1]. Caution in interpretation of the data is, however, again necessary since this effect may have nothing to do with the age *per se*, but may be the result of culling from the lower age-groups individuals which are naturally infertile and which do not appear in the older age-groups.

It is not possible in this study to compare accurately natural and artificial mating, but it is worth recording that, for the first 5 years included, all services were natural, whilst during the second 5 years an increasing proportion was by artificial insemination and by 1946–7 all mating was by artificial insemination except about 3 per cent. The conception rates may have been slightly depressed in 1943–4 and 1944–5 when artificial insemination was first used extensively, but in the last 2 years the

rates were fully up to those obtained when only natural mating was in use.

Proportion of effective matings.—In Table 2 all matings have been summarized to find out the proportion effective in each year, in each age-group, and where the natural or artificial method was used. This analysis bears out some of the conclusions drawn from Table 1, notably the lower percentage of matings which were effective in the younger cow-groups and the similarity in the efficacy of natural and artificial mating.

TABLE 2. *Summary of Matings*

	No. effective matings		*No. ineffective matings*		*Per cent. effective*	
	Natural	*Artificial*	*Natural*	*Artificial*	*Natural*	*Artificial*
Year						
1937–8	50	..	60	..	45·5	..
1938–9	47	..	76	..	38·2	..
1939–40	47	..	64	..	42·3	..
1940–1	48	..	58	..	45·2	..
1941–2	65	..	87	..	42·8	..
1942–3	32	19	14	26	69·6	42·2
1943–4	11	44	20	87	36·7	33·6
1944–5	7	45	11	45	38·9	50·0
1945–6	11	55	10	49	52·4	52·9
1946–7	1	70	3	46	25·0	60·7
Total	319	233	403	253	44·2	47·9
Age-group						
Maiden heifers	99	62	169	81	36·9	43·4
1st calf	62	37	79	54	44·0	40·7
2nd calf	53	48	67	39	44·2	55·2
3rd calf	44	35	41	30	51·8	53·8
4th calf	31	20	22	14	58·5	58·8
5th or later calf	30	31	25	35	54·5	47·0
Total	319	233	403	253	44·2	47·9

Potency of bulls.—The fertility of a herd of cows cannot be assessed independently of the potency of the bulls used on it. Unfortunately, however, the big variations in bull fertility due to age, season, and other factors, and the comparatively small number of cows served by one bull in a particular period make the appraisal of the influence of any one bull on herd fertility, at best, of doubtful accuracy. Analysis of the mating records also shows that no less than 21 bulls were at one time or another used on the herd during the 10 years under review. This number is somewhat inflated by the bigger number of bulls at the Artificial Insemination Centre used on the herd during the last 2 or 3 years.

Of the bulls used, 9 were used at least 50 times in the herd. The least effective of these provided 17 effective against 39 ineffective services, whilst the most effective bull provided 44 effective against 35 ineffective services. Although little significance can be attached to these data as measures of individual bull potency for the reasons set out above, they indicate that even with the most potent bulls nearly two services per conception were required when they were used for general herd work.

An endeavour has been made during the period to use to the maximum older bulls with daughter-records coming forward. As a result about half of the services were from bulls over 3 years old. These services were only slightly less effective than those by the 1-, 2-, and 3-year-old bulls. The older bulls' mating records, however, were biased by a large number of services by the old bull Redrice Darlington Chieftain, who remained moderately potent until 12 or 13 years old. In the first 4 age-groups, in each of which at least 7 bulls and over 100 matings were represented, the results were as follows:

	Effective matings	*Ineffective matings*	*Effective per cent.*
1-year old bulls . .	54	62	46·6
2-year old bulls . .	110	118	48·2
3-year old bulls . .	102	141	42·0
4-year old bulls . .	78	115	40·3

These data suggest that the rather widespread use of older bulls may have been a factor in reducing fertility rate.

Response to veterinary treatment.—Detailed records of veterinary treatment against infertility are available for each year since 1941–2, apart from the year 1944–5. Efforts were made to deal with both the problem of failure to come on heat and the problem of the animal failing to hold after persistent service.

In Table 3 a summary of the results of treatment of 33 cases in the first category is given. Fifteen of these animals were heifers, mostly between 24 and 27 months old in which oestrus had not been seen for

TABLE 3. *Result of Treatment of Cows and Heifers failing to come in Season*

Year	*No. treated*	*Days between treatment and 1st service*		*Number conceiving after*				*Number not conceiving after*			
		Under 42 days	*42 or more days*	*1st service*	*2nd service*	*3rd service*	*4th or subsequent service*	*1st service*	*2nd service*	*3rd service*	*4th or subsequent service*
1940–1 . .	1	..	..	..	..	..	..	..	..	..	..
		..	1	1	..	..	..	..	..	..	..
1941–2 . .	5	3	..	..	..	..	1	1	..	1	..
		..	2	..	1	..	..	1	..	..	..
1942–3 . .	8	5	..	2	2	1	..	..	..	..	..
		..	3	3	..	..	..	..	..	..	..
1943–4 . .	10	6	..	2	2	..	1	..	1	..	..
		..	4	2	..	..	..	..	1	1	..
1945–6 . .	5	3	..	3	..	..	..	..	..	..	..
		..	2	1	..	1	..	..	..	..	..
1946–7 . .	4	4	..	1	3	..	..	..	..	..	..
		..	..	..	..	..	..	..	..	..	..
Sub-total .	33	21	..	8	7	1	2	1	1	1	..
		..	12	7	1	1	..	1	1	1	..
Total . .		33		15	8	2	2	2	2	2	..
Per cent. .		..		45·5	24·2	6·1	6·1	6·1	6·1	6·1	..

several weeks in spite of daily observation. The 19 cows had also persistently failed to come on heat over an abnormally long period. With one or two exceptions veterinary attention was sought at not less than 3 months after calving. Treatments usually involved the injection of an oestrogenic hormone. Every one of these 33 animals came on heat after veterinary treatment. Twelve, however, were served more than 42 days after treatment, and it would seem probable that oestrus may have occurred naturally and not as a result of treatment. It should, however, be noted that in some cases where oestrus was induced service was withheld till the subsequent heat period. Table 3 shows that of the 33 animals treated 27 eventually conceived—22 to the first or second service. These conception rates are similar to the 'maiden heifer' group in Table 1, and the data suggest that service following induced oestrus or following delayed natural oestrus can be of normal efficiency.

Table 4 gives the results of veterinary treatment of 20 animals that had failed to hold to at least 3 services. Here the treatment usually consisted of uterine irrigation or hormonal treatment or a combination of both. The data suggest that in these cases conditions for pregnancy were more difficult to attain and only 9 of the 20 animals eventually conceived, although in 6 cases only one further service was given before disposal.

Pregnancy diagnosis.—Apart from the year 1944–5, pregnancy diagnosis has been made by a veterinary surgeon, since 1942, on most cows and heifers in the herd. Normally, this has been by palpation per rectum about 2 or 3 months after service. Since, however, the examinations were made in batches, some were done at less than 2 months after service and some more than 4 months after service. In most cases diagnosis was given definitely as pregnant or non-pregnant, but a few cases were described as 'probably pregnant' or 'probably non-pregnant', whilst in 5 cases only the person examining was not disposed to make even a doubtful diagnosis. A comparison of the results of the individual examinations with the actual state as indicated by the eventual production or non-production of a calf in each case is shown in Table 5. Of the 213 animals described as pregnant or probably pregnant, only 4 were eventually found to be non-pregnant. On the other hand, of the 31 animals described as non-pregnant or probably non-pregnant, 6 were, in fact, pregnant. It would appear, therefore, that a greater precision can be obtained in diagnosis of pregnancy than in the diagnosis of non-pregnancy.

Seven animals were definitely diagnosed incorrectly, and in order to find out if this was partly due to examining too soon after service, the period between service and examination has been determined and compared with the similar period for the animals correctly diagnosed. It is clear from this comparison that there is no strong correlation between incorrect diagnosis and period between service and examination. In fact, of 39 animals examined less than 60 days after service, only one was diagnosed incorrectly.

Discussion

This examination of the breeding records of a dairy herd over a 10-year period suggests that there is a danger of over-estimating the

TABLE 4. *Results of Treatment of Cows and Heifers failing to conceive to 3 or more Services*

Year	No. treated	Average no. ineffective services before treatment	Number conceiving after				Number not conceiving after			
			1st service	2nd service	3rd service	4th or subsequent service	1st service	2nd service	3rd service	4th or subsequent service
1940–1	3	5·0	..	..	..	..	2	..	..	1
1941–2	6	4·3	2	..	1	..	1	1	1	..
1943–4	2	3·0	..	..	1	..	1	..	..	..
1944–5	8	3·5	2	3	..	..	1	1	1	..
1945–6	1	5·0	..	..	..	..	1	..	..	..
Total	20	..	4	3	2	..	6	2	2	1

TABLE 5. *Accuracy of Pregnancy Examination*

	Diagnosed pregnant			Diagnosed probably pregnant			Diagnosed uncertain		Diagnosed probably non-pregnant			Diagnosed non-pregnant		
	Actually		Accuracy, per cent.	Actually		Accuracy, per cent.	Actually		Actually		Accuracy, per cent.	Actually		Accuracy, per cent.
	Preg.	Non-preg.		Preg.	Non-preg.		Preg.	Non-preg.	Preg.	Non-preg.		Preg.	Non-preg.	
1942–3	44	..	100	2	..	100	1	..	..	2	100	1	7	75
1943–4	40	..	100	2	..	100	..	..	..	1	100	..	7	100
1945–6	55	2	96·5	6	..	100	1	..	1	..	Nil	1	6	85·7
1946–7	52	2	96·3	8	..	100	3	1	2	..	Nil	1	2	66·7
4 years together	191	4	97·95	18	..	100	5	1	3	3	50	3	22	88

incidence of true sterility in a herd. Of 631 cows listed for service 75 failed to conceive, but it seems likely that up to half of these may have conceived eventually if served a sufficient number of times. A surprisingly large proportion of the cows conceived after 2 or 3 ineffective services, and it is probable that many of the 31 'barreners' sold after only 2 ineffective services would, by persistent service, have been got in-calf. In fact, other factors contributed to the decision to sell many of these animals, and, although lower fertility and consequent delay in conception may have finally decided their fate, there is clearly no justification for classifying all of them as disposals due to sterility. During the 10 years under review, we have records of only 12 cases which can be considered sterile in the pathological sense, although a few others may have escaped examination.

It seems reasonable to conclude that in the particular circumstances of the herd and period reviewed, the fertility of the cattle was no real barrier to the production of sufficient herd replacements, especially if at least 4 services had been provided for cows or heifers turning to the bull, and where veterinary attention was given to animals failing to come on heat. The question of whether it is economic to accept the cost of the longer average interval between calvings is, of course, dependent on the value of cull and replacement stock, the cost of food and labour, the value of milk, &c. This aspect is outside the scope of this survey.

Summary

1. A survey has been made of the breeding records of a large herd of dairy cows over a period of 10 years with the object of assessing the fertility of the herd.

2. Absolute sterility appears to have accounted for less than 5 per cent. of the herd each year but delay in getting cows in calf appears to have been a partial reason for disposal of a further small percentage.

3. Of 151 animals, all of which had been unsuccessfully served twice, 110 were eventually got in calf, 94 with either 1 or 2 further services.

4. Maiden heifers and 1st-calf cows showed a lower conception rate than older age-groups. This may not be due to age *per se* but may be due to culling of animals naturally infertile from the older groups.

5. Conception was achieved in 27 out of 33 cases that were treated for failure to come in season, but in only 9 cases out of 20 that were treated after persistently turning to the bull.

6. Pregnancy diagnosis by palpation per rectum has been about 98 per cent. accurate in the case of cows diagnosed pregnant and 88 per cent. accurate in the case of cows diagnosed non-pregnant. Accuracy of this order has been obtained in some cows about 2 months only after service.

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DISEASE-RESISTANCE IN POTATOES: AN HISTORICAL NOTE

R. N. SALAMAN

Wart disease was first recognized and scientifically described in Hungary by Schilbersky in 1896. In England its presence was recorded in 1901, and in Fife and in Wales in the same year by J. H. Wilson and Bryner Jones respectively. No mention of its presence in Ireland is found until 1908. There is good reason, however, to believe that these dates obscure the facts and that the disease was in fact present as early as 1876 in Haddington, Lincs., as well as in several places within the county of Cheshire.

It was not, however, until 1907 that the English authorities realized that the potato crop was threatened by a new and highly dangerous pest. The enactment of the Dangerous Insects and Pests Act of 1907 gave the Board (as it then was) the opportunity and the power not only to investigate the nature and extent of the trouble but also to take the necessary steps to combat the evil. In the following year G. C. Gough, an inspector of the Board, was allotted the task of making the necessary investigation. In the course of his tour of inspection he learned from Mr. Swindell, a farmer in Shropshire, that although nearly all his potatoes were attacked by the new disease, he had one variety which invariably escaped destruction. This variety was identified as Snowdrop. Gough immediately set to work to look for other varieties which might share this immunity, and added Golden Wonder, Langworthy, and Conquest to the list.

It soon became apparent that a complete examination of all known varieties would need to be carried out in order to differentiate, once and for all, immune from susceptible varieties. To this end trials on highly infected soil were set up throughout the country. Thus it came about that Gough's prompt reaction to a simple observation had far-reaching and important repercussions. From the point of view of scientific research perhaps the most important of these was the one with the least immediate external appeal. I speak of the creation of the Potato Synonym Committee.

Originally convened by the Royal Horticultural Society in 1915 and manned by persons representing the potato seedsmen and the agricultural official bodies in the United Kingdom, its work was directed by John Snell, a man of outstanding character who possessed a gift of fearless and uncompromising expression which was devastating in its effect. Snell disclosed the fact that the whole conception of potato varieties and their attributes in this country—and it was no better elsewhere—was in a state of utter confusion, in part due to the amazing ignorance of their material both on the part of the grower and the trade, and part to the less innocent devices of those who stood to gain by maintaining the *status quo*.

Snell died in 1920 and in the same year the National Institute of Agricultural Botany took over control of both wart testing and the

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determination of synonyms. Harold Bryan was appointed Director and Miss Whitehead (later Mrs. McDermott) his assistant, whilst I became Chairman of the Potato Synonym Committee, a position I have occupied ever since.

Having made the challenging statement that the Potato Synonym Committee was one of the most important moves in the new campaign, it is incumbent on me to make good my claim. I need do little more than state a few facts. The famous variety Up-to-date was found to have as many as 200 synonyms, and not infrequently the same dealer would market it under as many as six different names, each of which purported to represent an independent variety and often one that had never been offered to the public before. Thus out of the same field, indeed often out of the same bag, the public would be offered a range of varieties bearing attractive names and endowed with a range of qualities appropriate to the prices demanded. The varieties Abundance and British Queen mustered some 70 synonyms apiece. Less popular varieties had correspondingly fewer frauds perpetrated on them. Catharsis was an essential preliminary, for it was only when this unpleasant task was accomplished that intensive *ad hoc* research on varietal behaviour could be profitably undertaken or its results safely accepted.

Important scientific work on wart was delayed by the First World War but, prior to that, preparatory official action had been taken. The urgency of the threat to the potato culture by the rapid spread of wart disease throughout the country demonstrated the necessity for the establishment of suitably equipped stations throughout the United Kingdom, where scientific staffs would be ready to deal with dangers of this kind. To meet this end provision was made by the Development Commission in 1911.

In 1921 Miss K. Curtis [1] completed her fundamental research on the study of the fungus itself, an indirect result of which was the development of the glasshouse method of testing wart susceptibility-immunity. This was evolved in Germany by Spieckermann and Kotthoff [2] and Köhler [3, 4], in England by Miss Mary Glynne [5] at Rothamsted, and H. Bryan and Mrs. McDermott in Ormskirk [6].

The genetics of resistance to wart disease in the potato was first studied by J. W. Lesley of Cambridge and myself [7, 8] in Barley, Cambridge, and Ormskirk. It was shown that there were at least two dominant factors controlling resistance and that another factor might inhibit it; hence whilst it was easy to obtain immune seedlings from immune parents, it was equally possible in certain cases to obtain a small proportion of them from susceptible ones. In any case the use of one susceptible parent, if it was the conveyor of characters otherwise desirable, was by no means to be excluded.

Breeders have ever since confined their attention to the production of wart-resistant varieties and have rejected seedlings if susceptible, no matter how richly endowed in other respects.

The war against *blight* of the potato—so brilliantly told a few years ago by E. C. Large [9]—has of late years assumed a new direction, as Black has shown. The creation of blight-resistant varieties has been the

potato-breeder's dream ever since 1845 when *Phytophthora infestans* first attacked the potato in epidemic form. The earliest move in this campaign was taken by the Rev. Chumley Goodrich of New York who in 1857 imported certain tubers of a cultivated variety from Panama. To the resulting clone he gave the misleading title Rough Purple Chile. From this Panama stock, through its direct selfed descendants, Garnet Chile, Early Rose, and Peerless, the new blood spread throughout the potato cultures of both hemispheres. Unfortunately neither Rough Purple Chile nor any of its descendants were endowed with the least genetic resistance to blight, nor should we to-day expect it to have been otherwise, seeing that the Panama stocks were examples of the *S. andigenum* group of potatoes, in none of whom has any trace of resistance been discovered. At Cambridge some 150 varieties were tested before the outbreak of the last war and many others since, with completely negative results.

It may be recalled that as far back as 1830 a variety of similar *S. andigenum* stock had been introduced under the name of Daber; its blood has also entered into the ancestry of many varieties but failed, as might be expected, to convey any immunity to its offspring.

Further efforts to introduce the blood of wild species into our domestic stocks were made in the early decades of the present century, notably by the Rev. Aikman Paton, Mr. Arthur Sutton of the firm of Messrs. Sutton & Sons, and Dr. J. H. Wilson of Aberdeen, none of whom succeeded in demonstrating either the presence of specific resistance to blight nor in rearing a seedling of any economic value from such wild stocks.

Before passing to what must be regarded as the opening of a new chapter in the fight against blight, mention should be made of the few varieties which in the last 50 years or so won a fleeting reputation because of their resistance to disease. The best known of these was the Champion, produced by John Nichol and introduced in 1869. About the year 1877 it began to acquire a reputation for resistance to blight, and in the serious epidemic of 1879 its resistance, though not absolute, was, in relation to other varieties, quite remarkable and was maintained for the next 30 years. When at a later date this variety had become generally infected with the X virus its cropping capacity was reduced and its resistance to blight became less obvious. Other varieties, such as Champion II, which was known in 1909 as Clifden Seedling, and Leinster Wonder introduced in 1910, also exhibited a certain degree of resistance to *Phytophthora infestans*. The immunity, such as it was, exhibited by these latter varieties, as probably that displayed by Champion I also, was associated with extreme late maturity and it is likely that it may have been due to a physiological reaction of the growing plant rather than to any inherent genetic quality; to the same cause may be ascribed the fact that all 'earlies' and 'second earlies' of hitherto known varieties are particularly susceptible to blight. Extensive tests undertaken in Cambridge by my colleagues and myself showed conclusively that there was no evidence of inherent resistance to the common blight to be found in any of the domestic stocks or their seedlings which came under examination: they

all behaved in the same manner as the South American *S. andigenum* varieties to which I have already referred.

We may now turn to the discovery in the potato of a genuine and inherited resistance to blight.

In 1906 I acquired from Kew a few tubers of what purported to be *S. Maglia*, a South American species with a chromosome-content 2N = 36. Inasmuch as the tubers sent were white and those of *S. Maglia* should be purple, it was obvious that an error had occurred. My friend Arthur Sutton identified the plants with one he had grown for many years and had known as *S. tuberosum*. This, too, was shown to be erroneous a few years later by Berthault, who regarded the form as a distinct species and named it *S. edinense*, which was yet another mistake. As a result of intensive genetic research I was able to show that *S. edinense* was not a true species but a hybrid between a domestic European type and the wild Mexican species, *S. demissum*, a fact which was confirmed cytologically by Mary Campin.

Arthur Sutton, who had had the same stock under observation for some 20 years, informed me that he had never seen it attacked by blight, and indeed in Barley in 1906 the plants remained free from blight, but in 1907 a slight touch of disease in the haulm was observed, whilst in 1908 the attack was rather more severe, though at no time were the tubers ever attacked. It was in the latter year that the plants bore several naturally set berries.

In 1909 40 seedlings were raised in a year of exceptionally severe and widespread blight: 33 of the seedlings succumbed, 6 were entirely free from any sign of infection, and one had a few minute spots on a few leaves. In 1910 blight was once more rampant: the 7 resistant plants, which were planted in the midst of a group of heavily infected Abundance plants, remained unscathed. In the same year numerous crosses were made between the resistant seedlings and domestic varieties. In 1911 a record of the events referred to, the first example of genetic resistance to blight, or indeed to any other disease of the potato, was published [10].

One of the *S. edinense* seedlings was grown for 17 years continuously at Barley, its tubers being left in the ground all the winter, during which time it showed no sign of blight. It succumbed eventually, however, to leaf-roll.

At the same time as work was proceeding with the so-called *S. edinense* crosses, selfed seedlings of *S. demissum* which had been introduced under the mistaken name of *S. utile*, were under observation at Barley. It was noticed that they, too, were quite unaffected by blight in the open and hybridization was undertaken in 1913. In 1914 hybrid seedlings of *S. demissum* and *S. tuberosum* were grown in my garden at Barley. Not much was done during the war years but research was resumed in 1919 and a deliberate effort made to combine resistance to blight and wart disease, and tolerance to virus disease, with good field and table qualities. In 1926 representative stocks of the resistant strains were removed to the Potato Virus Research Station at Cambridge. In 1936 small plots of selected 'resistant' plants derived ultimately from the original 1914 crosses were growing there. About a month after neighbouring plots of

domestic varieties had been struck down by blight, the 'resistant' stocks became seriously infected. Suspecting that a new biotype of the fungus was involved, I persuaded my colleague, Miss O'Connor, to investigate, with the result that a new biotype was isolated and cultured. This, O'Connor called *Phytophthora infestans B*, as opposed to the common form which she designated 'A'.

Miss O'Connor then proceeded to search amongst the various stocks of wild and hybrid potato species then growing in the Station's glass-house and discovered a hybrid variety which came to us from Prof. Knappe of Poland, via America, under the name of 'Aya Papa'; it proved to be immune to Blight B. The new source of resistance was then introduced by hybridization into our stocks.

In 1941 Hawkes and Howard [11] showed that the source of our 'B' resistance had been wrongly named and that it was in fact an F_1 hybrid of *S. demissum* and a domestic potato, and hence closely akin to the so-called *S. edinense* with which our tale began.

I have recorded in some detail the several errors of identification in the course of my 33 years' research on blight resistance because they illustrate two points—the one that our knowledge of the taxonomy of the potato in the early decades of the century was very faulty, the second that we can learn much from our errors if we have the courage to recognize them.

Whilst the work described above was being transferred from Barley to Cambridge research in Germany was initiated by Broili [12] who made use of *S. edinense* and was pursued by Vorwinckel [13], who found that whilst no domestic stock showed any resistance to blight the offspring of a cross between a domestic and an unknown wild potato did do so. The resulting 'W' races, as they were termed, became the subject of further research by K. O. Müller which has been pursued by him till the present time. Using varieties of *S. demissum*, Müller has in a long series of papers enlarged our knowledge both of the *Phytophthora infestans* biotypes, of which he recognized 13 or more, and the nature of the reactions they excite in the resistant stocks, but whether he is correct in ascribing the resistance they exhibit to a super-sensitivity requires confirmation.

From 1921 onwards representative tubers of my hybrid stocks were sent to Northern Ireland to be grown under the care of the now famous potato-breeder, Mr. John Clarke, and there for all practical purposes they have continued to behave as blight-resistant varieties.

During the Cambridge period of my work it soon became necessary to devise a quick method of blight-testing. The problem was satisfactorily solved by placing single leaflets in a damp atmosphere under glass whilst their surfaces were sprayed with emulsions of 'A' or 'B' blight spores; in this way the reaction of large numbers of seedlings to any number of fungus biotypes could be determined in 7 days. On retiring in 1939, all my blight-resistant stocks were handed over to the Plant Breeding Institute, Cambridge.

Virus disease.—The study of plant-virus disease is of relatively recent origin. Though Appel had during the first decade of the century devoted

much study to leaf-roll, which then and for many years after was regarded as a disease induced by a fungus, it was Orton of America who first described it as a virus disease in 1914. The first serious attack on the problem of virus disease in the potato was made by Quanjer at Wageningen in Holland in 1913, the work of whose Station remained for many years a source of inspiration to workers throughout the world. It should, however, be remembered that the study of virus disease as such originated with Iwanowski's observation on Tobacco Mosaic in 1896, and that for many years it was the plant pathologists the world over who were the pioneers in virus research.

The first place in the British Empire in which the virus diseases of the potato were studied was in Prince Edward Island, Canada, where the late Prof. Paul Murphy had in 1915 migrated as Plant Pathologist. In 1921 he returned to Dublin and with his assistant, now Prof. R. McKay, initiated his research with an investigation of potato crinkle and its causal agents. A year earlier Kenneth Smith and Holmes-Smith had received appointments in the University of Manchester to investigate potato curl, and it was there that the former discovered an inclusion body in the cells of a potato leaf infected with 'mosaic'. What these early undertakings lacked in size, equipment, and finance, they more than made good by the skill and enthusiasm of their staff.

It was in 1926 that the Potato Virus Research Station opened at Cambridge, with myself as Director. Here it was that Kenneth Smith discovered the existence of viruses X and Y; Le Pelley and myself that of paracrinkle, and Bawden that of Virus B—to mention but a few of the earlier landmarks in the virus research of the potato.

As regards disease-resistance, and more especially that exhibited towards infection by the X virus, the necrotic effect induced by the X virus in such plants as Epicure, Arran Crest, and King Edward was recorded by myself and Bawden in 1932, and in his text-book of Plant Virus Disease, 1937, Kenneth Smith points out that the reaction of 'extreme susceptibility really means a practical immunity, since the plants are either healthy or killed outright'.

The discovery that a mild form of infection induced by one of the X virus protects a plant against the attack of the more virulent forms of the same virus was made by me in Cambridge in 1933 [14]; the similar one that a mild type of the Y virus will protect against a more virulent one [15], though unlikely to have any importance in the building up of new virus-resistant varieties, revealed a reaction which plays a vital role in Nature, whereby such varieties as Up-to-date are protected from attacks which would otherwise be fatal.

Earlier in this essay I emphasized the importance of the work done by the Potato Synonym Committee in bringing order into the overgrown family of potato varieties; now, as I close, I would equally commend the outstanding work of J. G. Hawkes, who has done a similar service—though under quite other circumstances—for the whole family of *S. tuberosa*. Hawkes and E. K. Balls conducted the expedition sent out under the auspices of the Commonwealth Agricultural Bureaux, to search the Americas for all available sources of the potato and its near relatives.

Following on the lines of the Russian Expeditions of 1925–32, they have brought many new species to our knowledge. Hawkes and his colleague C. M. Driver, as well as others working in the Imperial Bureau of Potato Research at Cambridge, have compiled a complete taxonomic survey of all the known species of tuber-bearing *Solanums* and have initiated an examination of the physiological characters of each species, so that from now on we can to an ever-increasing degree ascertain at a glance which species is endowed by nature with resistance to frost, to blight, to wart, or even to the attacks of the Colorado beetle.

In this brief survey of the earlier work which has gone to make the background against which the important researches outlined by Dr. Black [16] is being built up, I trust I have said enough to show that scientists in Great Britain have played no unimportant part in laying the foundations of the great enterprise now on foot, which is no less than to build up enduring disease-resistant stocks of one of the world's most important foodstuffs.

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PLANTING DATE AND COTTON PRODUCTION IN THE BUGANDA PROVINCE OF UGANDA

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Introduction.—Two distinct rainy seasons are experienced each year over most of Buganda. The first, starting with the vernal equinox, is usually more reliable than the second, which synchronizes with the autumnal equinox. Perennial crops, which normally require a higher annual rainfall, may be cultivated as a result of this extended though relatively low rainfall. During either of these seasons, however, rainfall may be inadequate for some annual crops.

Buganda is almost exclusively an agricultural community so that food crops are of primary importance. These must be planted with the onset of the first rainy season. Although cotton is the most important cash crop, it may be planted then only during the harvest period of the main food crops, or with the onset of the second rainy season.

Superficially the most convenient planting period for cotton appears to be with the onset of the second rains, when all the main food crops would be harvested. However, field experiments by the Department of Agriculture lasting several years [1] have provided consistent evidence in favour of May or June planting within the limits of May to September. Plots sown at the different planting dates were contiguous in all of these experiments, so that insect migrations from early- to later-sown cotton may have produced a consistent bias in favour of the early-sown cotton. Insects—notably *Lygus vosseleri*—might lead to considerable crop loss and would, if reinforced by such migrations, seriously affect the results of the trials. One of the purposes of this paper is to determine the extent to which such a criticism may be valid.

Increased cotton production—particularly at this time—is one of the important aims of the Department of Agriculture. The average annual production of the Protectorate is about 280,000 bales of lint. Buganda produces about 113,000 and is at present the most important producing area. Production during recent years has shown a marked decline. Plant diseases and insect pests cause many crop losses, which will be investigated later. However, the urgency of the problem demanded that data be reviewed to indicate the measures which could be taken to increase production under existing conditions of plant disease and insect-pest attacks.

Meteorology.—Summaries of monthly rainfall for some stations of the Protectorate have been given by Walter [2]. More recently Henderson [3] has given a summary based on additional data. The outstanding feature of the equatorial Uganda climate is the division of annual rainfall into two well-marked seasons. Rainfall is low during June and July over the region nearest the equator; farther north its distribution tends to become unimodal with no well-marked dry period during these months. The extreme southerly areas, such as the adjacent part of Tanganyika, show the reverse. Here the two rainfall peaks tend to widen and the peaks

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themselves to converge at the two ends, so that rainfall again becomes unimodal. The mid-year dry period for the southerly areas is as severe as the end-year dry period of the more northerly areas.

The main cotton-growing areas of Buganda Province lie within the limits 1° N. and 0° 45′ S. Superficially the annual rainfall of 40 to 50 in. appears to be adequate for most crops. Each of the rainy seasons may have 20 to 25 in., and local experience has shown that rainfall during either of these may be marginal for certain annual crops.

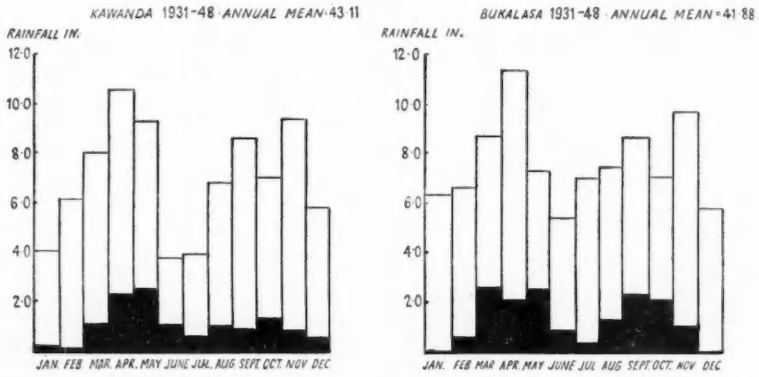

FIG. 1. Fiducial limits (10:1) of monthly rainfall at two stations in Buganda.

Reliability of rainfall, where the total is marginal, is clearly most important. An attempt has been made to demonstrate the probable monthly fall during the two seasons. Two stations were chosen. One lies within the best producing area and has both greater annual rainfall and less severe mid-year dry periods. This station—Bukalasa—was formerly the main cotton-breeding station of Buganda. The second station—Kawanda—is now the most important research station of the Protectorate and represents large areas of the south-west, having usually a relatively severe mid-year dry period.

Statements of probability may, of course, be derived only from frequency distributions at least approximately normal in form. Since frequency distributions of monthly rainfall tend to be demonstrably skew, a transformation of these data was essential. A statistical device, in this case $\sqrt{(x+0{\cdot}5)}$, led to a frequency distribution approximately normal in form. Statistics were calculated from these transformed data and 10:1 fiducial limits are shown in Fig. 1. Minimum rainfall expectation is given by months for 9 years out of 10, and is shown by blocking. Evidently in both areas the first rainy season is fairly reliable. Rainfall during the second rainy season is demonstrably unreliable at Kawanda, though at Bukalasa the second rains are shown to be almost as reliable as the first rains.

Variety-trial centres, distributed throughout the Province, may be grouped into two main areas each represented by the experiment stations

previously mentioned. Data from these centres are summarized in Table 1 according to the criteria: severity of drought during June and July, and reliability or otherwise of the second rainy season.

TABLE 1. *Some Rainfall Data at 11 Centres in Buganda. Monthly Rainfall in inches*

Locality	*Alt. (ft.)*	*Rainfall from Jan. to May*	*June*	*July*	*Rainfall from Aug. to Dec.*	*Annual mean*	*Number of years*
(*a*) *Where late rains are reliable*							
Bulindi .	3,400	21·58	3·93	3·48	24·72	53·71	11
Kalagala .	3,600	20·26	3·44	2·36	21·20	47·26	11
Bukalasa .	3,700	20·82	3·28	3·07	23·29	50·46	26
Nakifuma .	3,700	26·36	2·29	2·99	20·62	52·26	8
Mukono .	3,884	27·89	3·94	1·86	22·79	56·48	12
(*b*) *Where late rains are unreliable*							
Kabasanda .	3,800	20·54	2·67	1·86	23·41	48·48	11
Nkozi . .	3,900	20·93	2·58	1·12	17·15	41·78	11
Kawanda .	3,924	19·91	2·36	2·04	18·80	43·11	12
Bukomero .	4,000	18·72	2·31	3·47	22·12	46·62	8
Kyanamukaka	4,000	26·74	2·41	1·06	15·50	45·71	11
Kakumiro .	4,500	19·10	2·98	2·41	27·91	52·40	21

Table 1 shows that rainfall for some stations is marginal during both the first and second rainy seasons. Further, the comparative failure of June and July rainfall is most striking in areas with unreliable second rains. Rainfall during June and July, over the area of which Bukalasa is typical, may on the other hand be 6 in. or more.

The primary importance of food crops in predominantly agricultural areas delays the preparation of land for cotton. During May—the first month available for this operation—rainfall is adequate for the whole of Buganda. June rainfall is concentrated during the first half of the month and may therefore be considered as the decline of the first rainy season. Rainfall during July falls in the latter half of the month and usually indicates the onset of the second rainy season.

Should circumstances delay planting of cotton beyond May or early June, some difficulty might be experienced, in one area at least, in establishing the cotton during the latter part of June or early July. This risk is less for the areas with more reliable second rains. Where cotton must await suitable conditions for planting, the data show also that rainfall during the second rainy season may be inadequate for growth and maturity. Clearly these rainfall data suggest separate optimum sowing dates: late May or early June for the area of which Kawanda is typical, and up to the end of June for the Bukalasa group.

Temperature effects provide additional evidence in favour of these suggested planting dates. Moreau [4] has suggested that cloud and mist are likely to be of great biological importance at altitudes exceeding 3,000 or 4,000 ft. Table 1 shows that cotton is grown in Buganda at altitudes of not much less than 4,000 ft. Evidence of the protracted

growing season, partly resulting from climatic effects, has been adduced for the Kawanda station [5]. Here it was shown that mean daily hours of sunshine were as low as 3·3 for July and 3·0 for August. Corresponding average temperatures were 68·5° F. and 69·5° F. By contrast, temperatures in North Carolina for the same months, though at a later stage of growth, are 74·0° F. and 76·9° F. Sudan average temperatures during these months are 84·6° F. and 89·2° F.

The average number of days-to-first-flower is an important factor in determining the length of the cotton-growing season. The peak of the main flowering flush occurs in Buganda at about 90 days, although occasional flowers appear as early as 70 days in some areas. Varieties from the Sudan, where the average days-to-first-flower is about 70, do not reach their maxima before existing local varieties. Further, the earliest date-to-first-picking for May-sown cotton is about 175 days. Sowings in July tend to be about a fortnight earlier. Experimental plantings during the relatively warmer months of August and September fail to mature before the onset of the first rains of the next season. Therefore, although the extremes of temperature may not be great, they may prolong the growing season under Uganda conditions, compared with those experienced in other important cotton-growing countries.

Inferences arising from these meteorological data may now be summarized. The necessity for growing food crops restricts the possible planting months for cotton to the period starting in May. For certain areas, rainfall considerations restrict this period to late May and early June, or late July and August. Sowings in August may have adequate moisture during early growth but prevailing low temperatures result in a long cropping period. This also applies to May-sown cotton. However, the possible failure of the second rainy season involves a considerable crop risk with August-sown cotton, whereas May-sown cotton always matures before the onset of the next rainy season. On theoretical grounds, and with existing late-maturing cotton varieties, success is not likely to result from the apparently simple expedient of planting with the onset of the second rainy season.

Experimental Evidence

(*a*) *Sowing-date experiment.*—Formal sowing-date trials over several years have been summarized by Nye, Hosking, and Jameson [1]. There is a striking unanimity indicating the success of the May- and June-sown over the later-planted cotton. However, Jameson [6] has suggested that these results '. . . may have to be accepted with reserve in view of the possibility of cross interference by diseases and pests between adjacent plots . . .'.

A new type of experiment was designed to consider further the optimum time of planting in relation to crop losses due to insect interference. This experiment, based on one previously tried by officers of the Empire Cotton Growing Corporation in Nyasaland, had 'staggered' date-combinations at different localities. There were also two other important considerations that governed the new design. First it was accepted, for Buganda at least, that planting dates earlier than mid-May would

have but limited practical application. Secondly, with isolated plots that might avoid the build-up of insect populations, differences of locality would possibly be greater than differences resulting from the various planting dates. This necessitated a rather complicated, but unavoidable, least-squares solution, to estimate the probable differences due to the various planting dates.

The experiment was laid down at Kawanda in 1946. Sowings were carried out at three successive dates, separated by intervals of a fortnight, at each of eight localities with a two-thirds overlap between successive

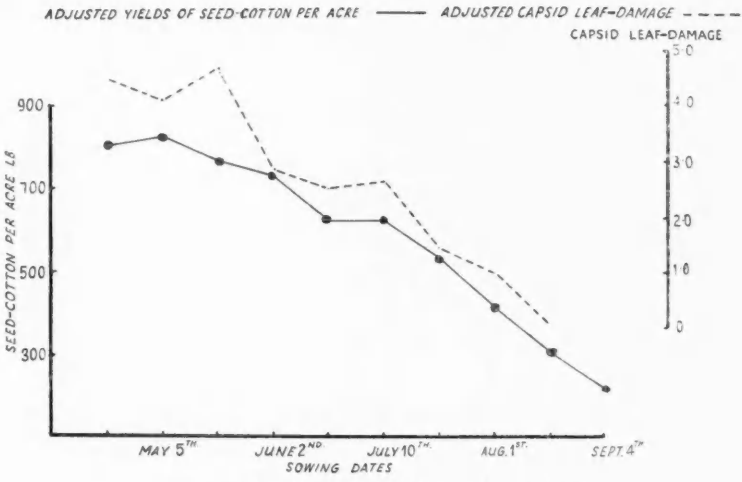

FIG. 2. Sowing-date trial, Kawanda 1946–7.

localities. That is, dates 1, 2, and 3 were used at the first locality; dates 2, 3, and 4 at the second locality; dates 3, 4, and 5 at the third locality, and so on. This design allowed for 10 planting dates spread over an 18-week period. Four replications were used at each locality, with the three dates at each locality being used in each replicate. Spatial isolation on the Kawanda station was necessarily limited, but was considered adequate.

Where locality differences are likely to be large, it might be expected that differences due to various planting dates could not readily be demonstrated; this was in fact one of the weaknesses of the first design of this type, and necessitated the least-squares solution previously mentioned. To evaluate true differences between yields at successive planting dates, it was necessary to adjust average yields for differences among localities. The least-squares solution could be avoided only if there was good evidence of the non-existence of locality differences. Full experimental details are given by Anderson and Manning [7].

Adjusted yields of seed-cotton per acre for the Kawanda sowing-date trial are shown in Fig. 2. Capsid leaf-damage counts are also given.

The decline of seed-cotton yields from cotton sown in May to September confirms the conclusions drawn from previous sowing-date experiments. Anderson and Manning [7] concluded that the optimum planting date was somewhere near the first planting date (May 1). Also that this optimum was poorly determined because there was no significant decrease in yield until the fifth planting date (June 26). There was no significant interaction between treatment and locality, i.e. the cropping capacity for any one sowing date did not differ markedly whether it was first, second, or third in a set of plots.

Capsid leaf-damage counts are a rather crude measure of the potential damage that has been attributed to *Lygus vosseleri*. Small but statistically significant negative correlations with yield have been recorded. Taylor [8] has indicated that in the 'elephant grass' (*Pennisetum purpureum*) areas, of which Kawanda is typical, much of the damage associated with Lygus attack would be avoided if sowing of cotton began in June instead of May. Data shown in Fig. 2 confirm that the incidence of this pest, as indicated by leaf-damage counts, falls off rapidly after the middle of June. In this trial, however, it was concluded that there was no significant overall regression of yield on capsid leaf-damage. There was not, therefore, any serious insect migration from the first- to the last-planted cotton at any one locality, when only three dates were used at a locality. The indications were rather that the first plot planted at a locality tended to act as a buffer with the highest leaf-damage counts. This damage had little apparent effect on the overall yields.

(*b*) *District variety trials.*—These trials have been conducted over Buganda for about 15 years. Actual planting dates have been contingent on suitable rainfall and so tend to be distributed at random within the defined period May to August. Unfortunately there are large differences between localities which tend to obscure the smaller differences, due to the various planting dates. In addition, seasonal differences are also large.

The artifice adopted to overcome these difficulties was to arrange the trials into two groups according to the reliability of the second rainy season. An overall group-mean yield per acre for the period 1935–48 was then computed for each, and individual yields at the various dates were adjusted seasonally for their respective group-mean. By thus ignoring seasonal differences and those due to locality, this device provides a measure of differences due to dates. At the same time these derived yields have comparative value only.

Data and calculated polynomials are given in Fig. 3 (for the area with reliable second rains) and Fig. 4 (with unreliable second rains).

The theoretical curves for the area with more reliable second rains is shown to be at a maximum round about June 24, though the highest actual yields were obtained from plantings early in July. Very early and very late plantings are shown to lead to equally low yields. It is not surprising that the very early plantings lead to low yields, since the plants would then tend to mature during the rainfall peak of the second rainy season. The high yields of some July plantings are also interesting. It is a fair inference that these yields may result from occasional years when the second rainy season exceptionally favours this later planting.

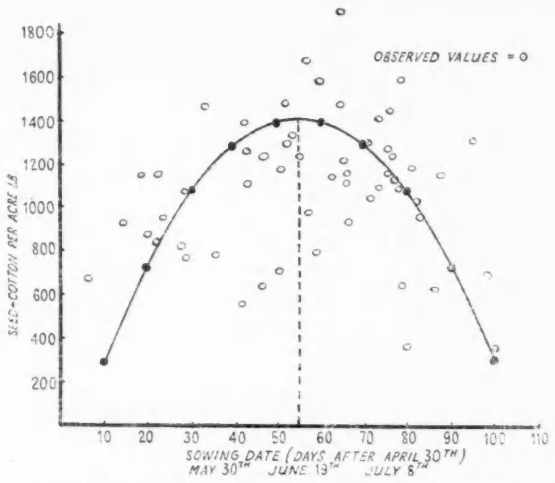

FIG. 3. Adjusted yields from five district variety-trial centres with reliable late rains. Data from 1938 to 1947. $N = 56$; theoretical curve from $3{\cdot}454x - 0{\cdot}288x^2 - 2{\cdot}856$.

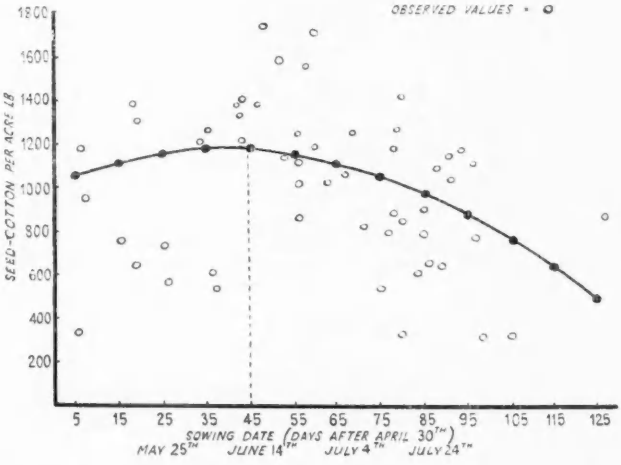

FIG. 4. Adjusted yields from six district variety-trial centres with unreliable late rains. Data from 1938 to 1947. $N = 54$; theoretical curve from $3{\cdot}866 + 0{\cdot}399x - 0{\cdot}045x^2$.

Fig. 4 shows that the poorly determined maximum of the theoretical curve occurs about June 14 for the area with unreliable second rains and low June–July rainfall. At first this appears to be inconsistent with the data from the most recent sowing-date trial at Kawanda—one of this group. Reference to Table 1 shows that rainfall for Kawanda during the period August to December is about 19 in., which may under certain circumstances be sufficient to interfere with maturity of cotton planted very early, i.e. May 1. The sowing-date trial was fortunate in having low rainfall during this period. Also it was shown that yield decline was not marked until a date near June 26. Over a number of years, then, this crop risk would be reduced where planting is sufficiently late to lead to maturity after the second rainy season, but early enough to have a reasonable expectation of rain during planting and early growth.

Sowing-date trials and District variety trials have provided strong evidence that low yields always result from very late-planted cotton. April- and early May-sown cotton also lead to poor yields though for different reasons. Evidently optimum planting dates occur within fairly narrow limits. Mid-June is indicated for the area with unreliable second rains, late June or early July is apparently the best planting period for the areas with more reliable second rains.

(*c*) *Multiplication scheme.*—Yields from the 20-acre increase area of the multiplication scheme at Kawanda have been recorded over the past eight seasons. This area is made up from fields of varying sizes and in various years of cultivation following an elephant-grass ley. Sowing dates from May to August must fit the planned rotation. Large fertility differences tend to obscure differences due to the various sowing dates. However, over the whole period, sowing dates tend to be distributed at random, so that derived weighted means have comparative value. Weighted mean yields per acre are given in Table 2.

TABLE 2. *Weighted Mean Yields per Acre by Months of 20-acre Increase at Kawanda. Cotton acreages in parentheses*

Season	Month of cotton planting					Seasonal Mean
	April	*May*	*June*	*July*	*August*	
1941–2 .	..	785 (18·0)	787 (1·9)	763	..	785
1942–3 .	..	1,008 (6·2)	977 (12·0)	763 (2·0)	..	965
1943–4 .	..	611 (6·1)	526 (10·9)	376 (3·9)	..	523
1944–5 .	241 (3·2)	333 (10·7)	886 (5·1)	712 (4·1)	..	510
1945–6 .	..	..	1,027 (6·5)	911 (10·7)	731 (3·3)	919
1946–7 .	..	585 (5·6)	624 (4·4)	572 (7·5)	573 (5·0)	586
1947–8 .	..	918 (5·2)	778 (0·4)	643 (16·1)	422 (1·9)	688
1948–9 .	..	704 (2·2)	879 (7·0)	590 (9·1)	591 (14·2)	660
Means .	241 (3·2)	690 (54·0)	816 (48·2)	668 (53·4)	593 (24·4)	696
% Stains .	36·1	11·1	4·9	9·2	10·4	..

Yields given in Table 2 confirm the inferences drawn from the small-scale and district variety trials. Yields from the 1945–6 season are interesting in that rainfall during August and September was unusually

favourable to the later-planted cotton. At the same time both the seasonal and average yields for June are consistently high. The high yields recorded for some May-planted cotton suggest that the optimum sowing-date would be nearer May than July, that is, the early part of June, and therefore support the inferences derived from the small-scale trials.

(*d*) *Accumulation of soil nitrogen.*—Griffith [9] has some unpublished data on total exchangeable bases for a wide range of Uganda soils. These indicate that although the nutrient status is generally low, there are no marked deficiencies of the major plant-nutrients. Preliminary evidence based on fertilizer trials conducted for the past three years [10] indicates that for most crops in Uganda, nitrogen is likely to provide the largest single stimulus to plant-growth and yield. Yield levels are generally low, so that responses are not at present of economic importance. Inconclusive yield-responses of cotton to nitrogenous fertilizers suggested that the limit of adequacy for this important plant-food may have been attained in at least one Uganda soil type.

Hardy [11] has shown that in the British West Indies appreciable quantities of nitrate-nitrogen accumulate in the soil under certain conditions. Further, that these accumulations may be important in the growth and development of the cotton plant. In the same paper Hardy has given some provisional limits of adequacy for the major nutrients; for cotton these are 40 p.p.m. NO_3 (incubation test), 40 p.p.m. P_2O_5 (Truog test), and 140 p.p.m. K_2O (exchangeable potash). Limits of adequacy for cotton have not so far been worked out in Uganda, so that Hardy's limits have been accepted as a working basis.

This important aspect has hitherto received little attention in Uganda but some data were available in the report of Martin and Griffith [12]. Moving averages of fortnightly determinations in the top soil of clean-weeded plots are shown in Fig. 5.

Fig. 5 shows two fairly well-marked periods during which the accumulation of nitrate-nitrogen in the top soil exceeded 40 p.p.m. Total rainfall recorded at the Kampala plantation, where these studies were conducted, amounted to 33·17 in. This is much below the average for that area though not much less than the average of which Kawanda may be considered typical. A close similarity is apparent between the general form of the nitrate curve and the annual rainfall distribution.

Recent investigations by Griffith and Manning [13] have confirmed the two peaked accumulations of soil nitrogen at Kawanda in 1948. Again, there was a marked similarity between the bi-modal rainfall distribution and the accumulated soil nitrogen. Both rainfall and accumulated nitrate were at a higher level than in the data recorded at the Kampala plantation. These most recent data showed that the second peak of nitrogen accumulations persisted until the end of September. There can be little doubt that on the elephant-grass soil types which were studied there are two periods during which the accumulated nitrogen exceeded the provisional limits of adequacy given by Hardy [11]; but there are also two periods during which the limit of 40 p.p.m. was not attained.

Were cotton planted at the end of May or during early June, flowering

would be expected to be at a maximum towards the end of August. Maskell and Mason [14] have shown that cotton buds and flowers are rich in nitrogen. From this it may be inferred that nitrogen-uptake is at a maximum during the main flowering flush. Therefore, where cotton is planted after the end of July and with a peak of flowering still not less than 85 days, the accumulation of nitrate-nitrogen would probably be less than these provisional limits of adequacy.

Although considerable further work must be conducted on this important aspect, there is sufficient evidence to show that reduced nitrate

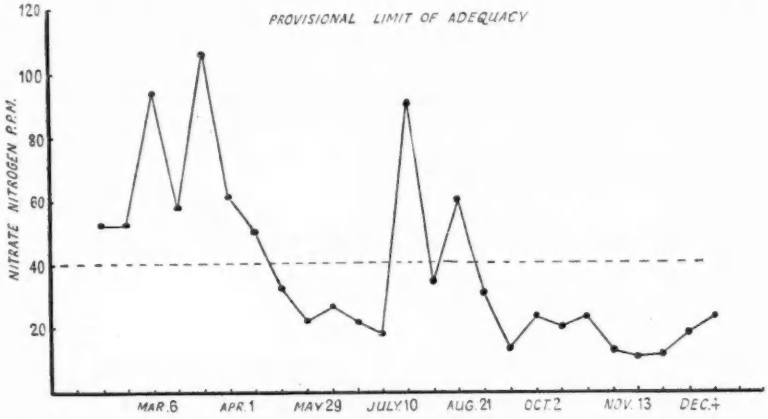

FIG. 5. Moving averages of fortnightly determinations of nitrogen-nitrates in top soil, Kampala, 1934.

status during later stages of growth of late-planted cotton may contribute to resulting low yields.

Provincial production.—It may be contended that experimental evidence adduced from relatively small-scale trials, where spatial isolation is necessarily limited, could not always be applied to an area growing about half a million acres of cotton. However, this acreage is made up of isolated plots seldom exceeding an acre. Also, since the question was of such importance, it was considered necessary to check the inferences drawn from these small-scale trials, and other theoretical considerations, with such data as were available from provincial production.

Estimates of cotton acreages planted each month are available for the past 20 years. Actual purchases of seed-cotton at ginneries are also available. Methods of estimating acreages have, however, not been consistent throughout the period. As a result, although production data are precise, estimates of yield per acre are therefore not directly comparable. Fortunately the acreage estimates were carried out on the widest possible scale so that satisfactory comparisons of the percentage plantings by months in each year may be derived.

An index was prepared of the percentage of the cotton crop planted each month in each of the 20 seasons. Planting returns are submitted by

the 25th of each month. From this it was assumed that the 10th would represent the average for that month. Arbitrary numbers 1 to 5 were then assigned to the months May to September. A weighted mean planting date was derived seasonally for the Mengo-Entebbe zone of Buganda, using the percentage planting by months and these numbers.

Mean planting dates, acreages, and annual production of seed-cotton for 20 seasons, are summarized in Table 3. Additional estimates derived from a multiple regression analysis of production on date and acreage, are also given; they illustrate the importance of these factors in determining total production.

TABLE 3. *Mean Planting Date, Acreage, and Production of Cotton for the Mengo-Entebbe Zone of Buganda*

Season	*Mean planting date**	*Acreage (in thousands)*	*Production (in thousand tons)*	*Estimated production†*
1928–9 . .	3·46	149·3	38·7	39·4
1929–30 . .	3·56	143·4	28·5	36·5
1930–1 . .	3·98	140·5	25·2	25·8
1931–2 . .	3·32	213·6	37·2	46·6
1932–3 . .	3·47	244·6	53·5	44·5
1933–4 . .	3·70	270·0	46·4	40·2
1934–5 . .	3·36	314·6	52·7	51·3
1935–6 . .	3·33	447·3	60·6	59·6
1936–7 . .	3·33	611·3	70·0	68·9
1937–8 . .	2·92	793·7	85·6	89·6
1938–9 . .	3·30	650·2	70·7	71·9
1939–40 . .	3·05	349·3	69·0	61·0
1940–1 . .	2·97	355·2	68·0	63·4
1941–2 . .	3·13	331·2	47·9	58·0
1942–3 . .	4·06	230·2	26·3	28·9
1943–4 . .	3·21	313·2	42·8	55·0
1944–5 . .	3·35	260·5	60·9	48·5
1945–6 . .	3·32	344·6	59·0	54·0
1946–7 . .	3·37	308·3	53·1	50·7
1947–8 . .	3·77	226·8	33·6	36·0
Means . .	3·40	334·9	51·5	

* Where May 10 = 1, June 10 = 2, &c.
† From $117{\cdot}936 - 25{\cdot}157x^1 + 0{\cdot}05683x^2$.

The total correlation between production and mean planting date was −0·784, and between production and acreage +0·841. Correlation between mean planting date and acreage was −0·571. This confirms that an early mean planting date does in fact lead to an increase in acreage. At the same time estimates of the independent effect of planting date and acreage were computed from the multiple regression analysis. The standard partial regression coefficient for yield on planting date was −0·451; that for yield on acreage was +0·583. This indicates that the date effects, other than their demonstrable influence on acreage, contribute materially to variation in production.

These data have the added importance of providing estimates of production when mean planting date and acreages are known. An

analysis of variance of total variation in production shows that about 85 per cent. ($R^2 = 0{\cdot}8458$) of the variation may be accounted for by the effects of mean planting date and acreage. Table 3 shows that the predicted estimate has in fact been reasonably close, except in the seasons 1941–2 and 1944–5. In the former season conditions were exceptionally unfavourable, and in the latter late rains exceptionally favoured the later-planted cotton.

Yields per acre would of course provide a more satisfactory comparison for a study of this nature, and it is therefore unfortunate that reliable estimates of such yields are not available over the whole period. Table 3 shows, however, that the earliest mean planting dates are associated with the highest production. At the other extreme, production associated with the very latest planting dates is invariably low. Clearly the earliest dates (2·92, i.e. about July 6) in Table 3 contributed to the large acreages; but almost equally important, these early mean dates also influenced yield independently of this effect on acreage.

In conclusion, it is now shown that these data indicate the advantages to be derived from late-May and June planting. This desirable aim is, however, very difficult to attain under conditions of large numbers of small plots widely scattered. Average planting dates about 3·00 (July 10) necessitate preparing and planting large areas in May. Also if planting during the latter part of August and September were curtailed, there would be a contraction of the planting season. These recommendations would lead to an average planting date near the middle of June, which has been shown to be the desirable optimum for this Province.

Summary and Conclusions

Food crops are of primary importance to the predominantly agricultural community of Buganda. They must be planted with the onset of the first rainy season, which over the greater part of the Province is more reliable than the second rainy season. Cotton may be planted during the period of low rainfall between the two rainy seasons, or with the onset of the second rains. Harvesting of cotton must take place before the onset of the next rainy season in March.

Annual rainfall occurs during two distinct seasons, each of about three months' duration. The first begins in March and the second in August. Practical implications arising from these separate seasons have been examined in some detail. For one area, covering the greater part of the Province, it has been shown that rainfall during the second rainy season may be inadequate for growth and maturity of cotton planted in August.

Prevailing overcast periods at this altitude and resulting temperatures —low for cotton cultivation—are shown to extend the period of growth and maturity both of local and introduced early-maturing varieties of cotton. This protracted growing period together with the erratic second rains are amongst the main reasons for the failure of cotton sown in late August and September.

Low rainfall during the latter part of June and early July further limits the planting period from which satisfactory yields may be expected.

Sowings in May are easily established but are often subjected to insect-pest attack (notably Lygus) and plant-diseases (such as *Xanthomonas malvacearum*). Lygus becomes progressively less through June and July sowings.

Previous trials conducted over several years indicated that May-sown cotton gave the highest yields. The validity of these results was questionable since contiguous plots were used for the different planting dates; insect migration could have taken place from early- to later-sown cotton. A new type of sowing-date experiment indicated that there was no evidence that insect interference contributed to the lower yields of cotton sown in August and September. Rather, the cotton sown in May and June had the highest Lygus leaf-damage counts. The optimum sowing date for this trial was near May 1, but yield decline was not demonstrable before June 26.

Cumulative evidence from further independent trials confirms the evidence adduced from previous departmental trials: the optimum sowing date for the area nearest the equator occurs during the early part of June; farther north in Buganda, dates as late as mid-July have also given high yields.

Cotton sown about these dates probably enjoys the additional advantage to be derived from accumulated nitrate-nitrogen, immediately before the main flowering flush.

Provincial production confirms the experimental evidence. An advance in mean planting date from mid-August to late June or early July would lead to a large increase in production as long as acreages were not reduced. Also, although the specific optima would be impractical to attain, the contraction of the planting season would result in an average planting date nearer to these optima.

Advances from varietal improvements, which would include breeding for resistance to plant-diseases and insect pests, and the small percentage increments expected from applications of fertilizers, are relatively insignificant compared with production increases to be expected from advancing the planting-date and a contraction at both ends of the planting season.

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PROLONGED DORMANCY OF DECIDUOUS FRUIT-TREES IN WARM CLIMATES

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The Phenomenon

THE members of the group of deciduous tree fruits, which include the apple, pear, peach, cherry, plum, and apricot, are all alike in that they require a winter dormant period for the proper development of their flower- and leaf-buds. Where they do not get sufficient chilling weather in winter, as happens in countries where winters are mild, deciduous fruit-trees exhibit the phenomenon known as prolonged dormancy [1, 2, 3] in which delayed foliation is the main symptom.

The seasonal alternation of growth and rest of deciduous trees was taken for granted by early European botanists. Forced by the cold of winter to rest, buds and seeds are stimulated into growth in spring by the milder weather, which starts the upward flow of sap from the roots. During the period of summer growth new resting buds are formed. With the cooler weather of autumn root-activity is reduced; the supply of water to the leaves fails, and, prepared by the formation of the abscission layer earlier, they fall during storms and after frosts. But this picture is incomplete. Thus, in uniform tropical climates some introduced deciduous species tend to behave as evergreens [4, 5]. Others may go into a state of dormancy and remain leafless—in such a condition, in fact, as can be brought about in the blueberry by transferring it to a greenhouse during active growth. Despite the warm growing-conditions of the greenhouse it will go into a state of dormancy in autumn, a state that will persist in the following spring and may continue for as long as a year [6]. Resting buds of many deciduous species cannot be forced into growth by simply transferring them to warm conditions during the autumn. Yet, at some time during the winter, after they have experienced the required amount of cold, such buds will respond rapidly to warmth [7].

Temperature is the main climatic factor governing the world distribution of deciduous fruit-trees. They are limited to regions having enough cold in winter to break the rest period, but not enough to injure the roots. Varietal differences make it difficult to quote exact figures for the chilling requirements of the different deciduous fruits. Most American peach varieties and European pears need 600–900 hrs. below 45° F. to end their rest period, and apples need 900–1,200 hrs. Certain peach varieties [8] and the oriental pears [9] need much less. Flower-buds, which generally need less chilling [10], may open before the leaves develop. In severely delayed foliation many flowers are shed before opening, or soon after setting, when there are not enough leaves to mature the crop. On one tree individual branches may be more or less affected; thus, one branch may still remain dormant while a second is in full blossom and a

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third carries leaves and fruits [11, 2, 1, 10]. Buds may develop only at the tip and base of a shoot, making it appear bare-necked. If flowering is spread over a long period the effectiveness of cross-pollination may be reduced [10]. Besides the immediate loss of the current season's crop caused by delayed foliation, there is a further potential loss in that buds whose dormancy is prolonged may fail to form wood for fruiting in the next season [1].

The problem of delayed foliation has arisen where attempts have been made to extend the range of cultivation of the deciduous fruits into tropical and subtropical climates. It has been reported in the United States from California [10] and the Southern States [2], in North [12], East [2], and South Africa [1], in India [5], Australia [13], and Palestine [7].

There are two distinct types of dormancy. Imposed dormancy is the state of quiescence experienced by the whole plant when external conditions prevent growth. True dormancy, or the period of physiological rest, seems to be due to internal changes; it begins with the formation of the resting bud, it is shortened by cold, and in temperate climates it ends during the winter. It is not systemic, for dormancy may be broken in a single bud by chemical treatment [14] or mechanical injury, or in the buds of a single shoot [6] without affecting the rest of the plant. In temperate regions dormancy imposed by cold restrains the activity of the buds after their physiological rest is completed; growth begins with the coming of spring and warmth. The subtropical and tropical limits for the cultivation of deciduous fruits are set by the absence of factors that end the period of true dormancy, which is prolonged after imposed dormancy has ended [11].

The unfortunate double use of the term dormancy is emphasized by the strikingly parallel behaviour of the seeds of many deciduous species that remain dormant, and will not germinate ordinarily, until 'after-ripened' by some weeks of cold. In nature this after-ripening is brought about by the seasonal changes, in the nursery by stratification. This necessary period of physiological rest is quite unlike other types of seed dormancy due to incomplete differentiation of the embryo, or to the restriction of the supply of water or oxygen by an impermeable seed coat [7]. Physiological dormancy of peach seed has been broken by sterile culture of the embryo, removed from its pit before ripening; but the seedlings so produced make very restricted, abnormal growth and soon resume dormancy, unless grown under continuous light [15].

In seeds and buds the necessity of a period of true dormancy at low temperatures prevents the development of new growth in autumn, in spite of the occasional occurrence then of temperatures that are high enough to end imposed dormancy in spring. When once the adequate chilling of winter has so altered buds and seeds that they will develop in the warmth of spring, there is less risk of damage to the tender growth by frost. Although the mechanism of this physiological rest is not fully understood, it does appear to be linked with the winter hardiness developed in deciduous trees [6].

Remedies

But whatever the fundamental reason for prolonged dormancy, its consequences are serious enough to the grower. What can he do to prevent it? The possible remedies fall under three heads: (i) the selection and breeding of resistant varieties, i.e. varieties that will emerge from dormancy without delay despite lack of chilling; (ii) orchard management, and (iii) spray treatment.

Selection and breeding.—American and South African work has shown that the most satisfactory remedy for prolonged dormancy lies in choosing those varieties with low chilling requirements which flower and break into leaf normally even after a mild winter. Deciduous fruits and their varieties differ considerably in their chilling requirements, the order in South Africa [3] being given as: grape, apricot, Japanese plum, peach, pear, and apple. There the grape can be grown where the average winter temperature (June–July) is above 54° F., whereas apples require an average temperature of about 45° F. during these same months. In the western Cape Province of South Africa where winter cold is the climatic feature which has the greatest influence on yield of deciduous fruit [3, 1], a limited number of varieties which are 'resistant', in varying degrees, to prolonged dormancy have been recommended to growers. Amongst these varieties are the following [1]. Peaches: Early Dawn, Boland, and Babcock (all highly resistant). Plums: Methley (almost immune), Santa Rosa, Kelsey, and President (all highly resistant). Pears: Keiffer (highly resistant), Packham's Triumph, and Winter Nelis (both fairly resistant). Apples are not recommended for planting outside the recognized apple area of Cape Province, but the following, none of first-class quality, are recorded as being fairly resistant to prolonged dormancy: Alma, Winter Banana, and Wemmershoek. In California the following, amongst others, are recorded as resistant. Peaches: Robin, Redbird, Weldon (all early), Hermosa, Sunglow, and Fontana (all mid-season) [16]. Plums, common: Tragedy and Sugar-prune. Plums, Japanese: most of these have moderate chilling requirements. Apricots: Newcastle, Blenheim, and Royal. Pears: P. Barry, Forelle, Flemish Beauty, Anjou. Apples: Hume, Wealthy, Early McIntosh, Winter Banana, White Winter Pearmain, and Wolf River. In the Kenya highlands, on the equator, where the problem of prolonged dormancy in deciduous fruits is a major one, the following are some of the varieties recommended for the elevations shown [2]. Apricots: at 8,000–9,000 ft. a.s.l.; Early Cape, Royal, Blenheim, and Tilton. Peaches: 5,000–8,000 ft.; Angel, Jewel, Babcock, Killicrankie, and Shackleford: 7,500–8,500 ft., Muir, Pallas: 8,000–8,500 ft., Mamie Ross: 6,000–8,000 ft., Hall's Yellow. Plums: 7,000–8,000 ft., Beckie Smith, Wickson: 8,000–9,000 ft., El Dorado: 7,000–9,000 ft., Hale, Methley, Jardine's Early, Purple King, Santa Rosa, Satsuma, Tagazine, Settler, Watson's Cropper. Pears: 7,000–9,000 ft., Keiffer, Le Conte, Packham's Triumph, Smith's Hybrid: 8,000–9,000 ft., Fertility, Jargonelle, Williams' Bon Chrétien. Quinces: 7,000–9,000 ft., Meeches Prolific, Orange Quince, Rae's Mammoth, Portugal. Apples: 8,000–9,000 ft., Ballarat Seedling, Christmas, Gravenstein, Sharpe's Early,

Syke House Russet, Spring-dale: 7,000–9,000 ft., Blenheim Orange, Cleopatra, Jonathan, King of Tomkin's County, Rome Beauty.

Orchard management.—Turning to orchard management, it has been shown that control of the water-supply (where trees are irrigated), shading, and pruning all influence dormancy.

(i) Water-supply: The degree of delay in the opening of flower- and leaf-buds is influenced by the experience of the tree in the preceding year: thus, after a warm winter, those trees which suffered from drought in the latter part of the preceding summer, and so lost their leaves early, may exhibit better shoot-growth and come into flower a little earlier than usual the following spring. The apple is particularly susceptible to dry periods and is prone to go into a state of dormancy under conditions of severe drought [10]. In North Africa, India, and elsewhere irrigation water is withheld in deciduous fruit orchards after harvest in order to induce dormancy. The method used in Bangalore,[1] India, is of particular interest since it is claimed to produce two crops of apples per year in a tropical area, where winters are warm. The method used is briefly as follows [5]. After harvest, irrigation water is withheld for about a fortnight and the soil surrounding the tree removed to a depth of 6 in., so that the leaves wilt; some fall and the remainder are stripped by hand. The exposed roots are then covered with sand and compost and irrigation is restarted so that the tree comes into bloom and produces a crop in the fifth or sixth month. The process is then repeated. In this way two crops are produced in 12–15 months. This practice does not conduce to longevity. It is interesting to speculate whether the necessary defoliation might not be more simply achieved by dusting with calcium cyanamide [17] or spraying with copper salts.

(ii) Shading: The influence of shade on the chilling requirements of deciduous fruit-trees is marked. In California it has been observed [10] that the longer a fruit-tree is shaded from direct sunlight during each mid-winter day the earlier will its buds open in spring as compared with buds on unshaded neighbouring trees. South African experience has also demonstrated the effect of shade in counteracting prolonged dormancy [18]. Despite this knowledge there appears to be no record of shade-trees being established in or around deciduous fruit orchards to assist in winter chilling. Winter fog, where it occurs, as in parts of California, is similar in its effect to shade [10]. The white-washing of trunks and branches will also assist in reducing the potency of winter sunshine [19].

(iii) Pruning: 'The pruning system used may have some influence on the opening of buds after a warm winter' [10]. Severe pruning encourages the growth of long shoots and it is in such shoots that the greatest delay in bud-opening occurs. 'Heading back to stubs in the top of the tree causes more long shoot-growth than cutting back to other branches' [10]. As a general rule any system which encourages long, late shoot-growth should be avoided.

Spray treatment.—The successful use of oil and/or chemical sprays for helping to break the resting period in deciduous fruit-trees after mild

[1] 12–15° N. lat., 3,000 ft. a.s.l.

winters is recorded from South Africa, California, and Palestine [20, 21, 22, 7]. In South Africa increases in fruit yields of up to 500 per cent. have been recorded as a result of winter oil-spraying [2]. The oil-spray is usually applied about a month before growth normally starts, the best results being obtained if the spraying is carried out after there has been some chilling weather. If it is done too early it may not be effective: if done too late it may delay bud-opening [10]. Oil spraying is now an established practice in parts of the U.S.A. According to one authority [23] it is doubtful whether its beneficial effects are due to its stimulating properties or to the control of diseases and pests which it effects. A stock mixture oil-spray can be made by dissolving 2 lb. of soft soap in 3 gal. of hot water and gradually adding 1 gal. of raw linseed oil, while agitating the mixture. One gallon of this stock mixture is added to 4 gal. of water for spraying [2].

Apart from the use of oil-sprays there are many other treatments known to break the resting-period in plants. These include treatment with: nitrate of soda [22], ethylene dichloride, ethylene chlorohydrin, ethyl iodide, sodium thiocyanate, thiourea, dinitro-*o*-cyclohexylphenol and dinitrocresol [14, 24, 25, 10, 7]. A 1 : 10 lime-sulphur spray is also claimed to be effective [26]. Most of these treatments are at present of academic interest only but dinitro-*o*-cyclohexylphenol (DNO) and dinitrocresol (DNC) have been used with promising results in the field. In Palestine 3-5 dinitro-*o*-cresol/mineral oil emulsion, containing 4 per cent. oil and 0·06 per cent. DNC, sprayed on apple-trees in February–March is reported to break the dormancy of the trees effectively. Further, each spraying was found to have a forcing effect, stimulating earlier foliation, blooming, and ripening, an effect which diminished with delay in the date of spraying. Experience in Palestine shows that the different apple varieties do not all react in the same way to this spray and the question arises whether prolonged dormancy is a single phenomenon or whether it involves more than one mechanism. The chilling requirements of varieties may represent a complex and not a single property [7]. All these methods of breaking dormancy by means of oil and/or chemical sprays are, of course, unnatural, and in some cases too drastic to be desirable. Their mode of action is still something of a mystery for it would appear that in no case has it been analysed [24]. It may well be that their application results in an activation or stimulation of plant hormones [27].

In conclusion, it would appear that whilst other remedies are palliatives the real solution to this problem of prolonged dormancy of deciduous fruits in warm countries can best be found through plant-breeding and selection.

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THE EFFECTIVENESS OF VARIOUS LIMING MATERIALS

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THE great majority of Scottish soils are acid and deficient in lime. Most of the soils in the north, for example, have pH values between 5·0 and 5·5, and under the rather high rainfall prevailing there are considerable losses of lime in the drainage in addition to that removed in produce sold off the farms. The results of Hendrick and Welsh [1] from the Craibstone lysimeters, for example, show that for a typical acid soil of granitic origin in the north-east the amount of CaO lost in the drainage ranges from about 70 lb. per acre per annum in the absence of added lime and manures, to about 110 lb. for manures alone, and 130 lb. for lime and manures. Thus, Ogg [2] estimated in 1942 that in Scotland as a whole about 2 million tons of calcium carbonate would have to be applied annually for 4 or 5 years to correct outstanding deficiencies, and that a further million tons annually would be necessary to make good current losses.

Although there has been a considerable revival of liming in Scottish agriculture during recent years, there is still a great need for a much more extensive use of lime. Advisory analyses of soil samples from agricultural land in Aberdeenshire, for example, show that the percentage of soils with a satisfactory lime-status is still only about 5, and that more than 40 per cent. require over 2 tons $CaCO_3$ per acre to bring them to a satisfactory level. This state of affairs is typical of most other parts of the country; its continuance is doubtless partly due to increased cropping and to higher yields and drainage losses following heavier applications of fertilizers, especially sulphate of ammonia. However, the fact remains that lime deficiency is still very widespread and is limiting production. Further, its importance is increased by the fact that it aggravates the extensive phosphate deficiencies which also occur and limits the effectiveness of applied phosphate [3, 4].

Since the demand, both actual and potential, for lime still exceeds the supply, it is important to make use of all suitable materials and, hence, to test the effectiveness of all potential forms. Such first-hand information is particularly desirable in view of the prejudices and doubts which still exist amongst farmers. Three field experiments were, therefore, started in 1944 to compare a range of liming materials, and the present paper deals with their effects on the yield and composition of crop, and on soil properties over a period of 4 years.

Experimental

Soils.—The three centres (Craigiebuckler, pH 5·3; Wedderhill I, pH 5·1; Wedderhill II, pH 5·0) were selected as being typical of much of the lime-deficient land in Scotland. The soil in each case is derived from granitic drift and contains about 12 per cent. clay, but the approximate

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organic-matter content (loss on ignition) varies from 10 per cent. at Craigiebuckler, which is a normal mineral soil, to 16 and 25 per cent. at Wedderhill I and II, respectively, both of which tend to be peaty.

Liming materials.—The materials tested together with symbols and analyses are given in Table 1. The magnesian forms, Nos. 2 and 9, were included largely to determine their effect on magnesium-uptake by the crops, because of the possibility that, although magnesium deficiency limiting crop-growth is not widespread in Scotland, the magnesium-content of the crops in some areas may have a bearing on animal health. It was also desired to obtain information concerning the prejudice existing against the use of magnesian lime [5], and to find out whether the magnesium would have a specific effect on phosphate-uptake. The magnesian lime, No. 2, had a satisfactorily high content of magnesium, but the magnesian limestone, No. 9, proved much lower in magnesium than expected and was not a great deal higher than some of the other materials, all of which contained some. The dried paper-works lime, No. 3, is a by-product of considerable local importance and is a reasonably fine material with about 50 per cent. passing the 100-mesh sieve. The calcareous shell sand, No. 4, represents the type of deposit found around the northern coasts of Scotland and is a relatively coarse material. The range of particle sizes in these deposits is usually within the following limits: 2–10 per cent. $>$ 2 mm.; 35–45 per cent. $<$ 2 $>$ 1 mm.; 35–45 per cent. $<$ 1 mm. $>$ 0·5 mm.; 5–10 per cent. $<$ 0·5 $>$ 100 mesh; 1 per cent. $>$ 100 mesh. No. 5, ground limestone, 70 per cent. fineness, is an example of a material commonly used in Scotland. The ground limestones Nos. 6, 7, and 8 were from carboniferous formations and the main object was to determine the relative effectiveness of the three sizes, especially the coarsest, because there is still some doubt as to the optimum fineness. The blast-furnace slag, No. 10, is described as a falling haematite slag; it consists mainly of calcium silicate and was included partly to see whether the silicate component would have any specific effect on phosphate-uptake. The materials were all applied on the basis of their total (CaO + MgO) neutralizing values, but for convenience the rates in the tables are given as the equivalent CaO.

Field technique.—The experimental design at Craigiebuckler was a set of 5 × 5 lattice squares with three replicates, three control (no-lime) treatments, and plots of 100 sq. yds. The results for two treatments, which involved phosphate in addition to lime, have been omitted. Both Wedderhill experiments were in the form of latin squares with plots of 87·5 sq. yds.

At all three centres the liming materials were applied on the ploughed surface in March 1944 and worked into the soil by the cultivations carried out before seeding. Suitable basal dressings of nitrogen, phosphate, and potash were applied for each crop.

At Craigiebuckler in 1944 the first cut of rye-grass and red clover contained a high proportion of weeds and was discarded, but yield data were obtained for the second cut in autumn. The first crop at Wedderhill was intended to be mangolds, but they failed to establish and both centres were ploughed and resown with broadcast turnips, the weights

of bulbs and leaves being recorded together. The subsequent crops and all the yield data are given in Tables 2, 4, and 6 (pp. 273, 274, 275).

Results

Yield data.—Except for the 1944 and 1945 crops in the Wedderhill experiments, there was a marked response to all liming materials. At Craigiebuckler liming produced a sevenfold increase in mangolds, about twice as much barley grain, and about one-third more hay; at Wedderhill the yields of hay were about doubled. These increases are by no means exceptional under Scottish conditions and illustrate very clearly the great returns from liming acid soils.

At Craigiebuckler the response to lime is marked up to 17·5 cwt. CaO per acre but above this it falls off considerably. Although the yields at the 35-cwt. levels are generally higher, the increases are statistically significant in only a few cases. Further, the yields obtained with 52·5 cwt. CaO per acre burnt lime are practically the same as for the 35-cwt. rate, indicating that there is no advantage in applying very heavy dressings of lime to this soil. Much the same applies to the Wedderhill I results in Table 4. These show that there is a large response to the 15-cwt. CaO rate of burnt lime, but although all the 30-cwt. levels produced higher yields the increase is significant only in the case of 20–40 mesh limestone in 1946.

The Craigiebuckler yields show sporadic variations between forms and the differences occasionally attain or approach statistical significance. But there is no major consistent trend in favour of any one form, and the differences generally are unimportant compared with the large response to lime.

The inferiority of the 35-cwt. rate of shell sand in the first year is confirmed by the results for the 17·5-cwt. rate, and it can be concluded that, initially, this relatively coarse material is appreciably less effective than most of the other forms. In subsequent years, however, it is well up to the average values for the others. The apparent inferiority of the 35-cwt. rate of 20–40 mesh limestone in the first year, on the other hand, is not borne out by the yields for the 17·5-cwt. rates, and there is therefore no conclusive evidence that its initial effectiveness is significantly inferior to that of the finer sizes. Similarly, the trend in favour of 20–40 mesh compared with 100-mesh limestone at the 17·5-cwt. rate in 1946–8 is reversed at the 35-cwt. level in 1946 and 1947, but reappears in 1948. This does not of necessity vitiate the significance of the trend at the lower rate because the relative long-term effectiveness of different sizes may depend on the rate of application, and the fact that the trend at both levels favours the coarse material in the last year may be significant. Further yield data are necessary before a final conclusion can be drawn.

The trend in favour of paper-works lime compared with most other forms is confined largely to the 1945 mangolds and is probably fortuitous, but this material shows consistently high yields and compares well with all other forms. The blast-furnace slag is also quite an effective form; except for the 1945 mangolds and anomalously low values for the 52·5-cwt. rate in 1944 and the 35-cwt. rate in 1947, it falls within the range

covered by the other forms. In general the magnesian lime and magnesian limestone also show consistently good yields.

The only statistically significant differences at Wedderhill are between ground limestone and shell sand compared with paper-works lime in 1946 at Wedderhill II (Table 6), but they are not confirmed in the next year. Otherwise, the yields for the different forms at this centre agree very closely. There are no clear trends at Wedderhill I (Table 4), but the results show that the ground limestones are at least as effective as burnt lime and that the two coarser sizes compare favourably with the fine material.

Crop analyses.—No samples were kept for analyses from the crops grown during the first year of the three experiments, but the nutrient contents and uptakes for the subsequent crops have been determined. In general there are no appreciable differences in the composition of the crops grown with the different calcium liming materials, and mean data for only one CaO-level are given in Tables 3, 5, and 7 (pp. 274, 275, 276). As with the yield increase, at Craigiebuckler there is a considerable increase in nutrient-uptake up to the 17·5-cwt. rate, but little or no increase above this level.

Considering first the calcium-contents of the crops, the Craigiebuckler results, Table 3, show that, qualitatively, the actual percentage of calcium tends to vary inversely with the increase in yield; thus, the percentage for the 1945 mangold crop, where there was a very large increase in yield, is markedly lower in the presence of lime; in the 1946 and 1947 barley, on the other hand, where the yield increase was much smaller, it is about the same or a little higher than the control, and in the 1948 hay, where the yield increase was relatively small, it is about doubled. The total uptake of calcium, however, reflects the yield increases and is much higher in the presence of lime, the total removal during 4 years being about trebled for the 35-cwt. rates. The magnesian lime shows consistently lower percentages and uptakes of calcium than the other forms, but the total CaO removal is still about twice that from the control. It is noteworthy that blast-furnace slag tends to show slightly lower uptakes than the other forms and that the yield-trend in favour of the coarser limestones compared with the fine in the last year is compensated by an opposite trend in calcium-uptake.

Except for the 1945 mangolds where the increase in yield was very high, the magnesian lime increased the percentage MgO in the crops. The increase in the 1946 barley is not pronounced, but the 35-cwt. rate about doubled the percentage in the 1947 barley and about trebled that in the 1948 hay. Similarly, the total MgO removal for this rate during 4 years is about four times that for the control and nearly twice that for the calcium forms. The magnesian limestone with its low magnesium-content, however, was relatively ineffective and hardly superior to the ordinary forms. The latter showed little or no effect on the actual percentage of magnesium, but caused a twofold increase in the total removal. This indicates that, as expected, magnesium deficiency is not limiting growth in the Craigiebuckler soil. The total removal for blast-furnace slag is again slightly less than for the others.

The K_2O percentages for Craigiebuckler show no appreciable effect of lime; the total uptakes therefore follow the yields and are much higher in the presence of lime, the total removal during 4 years being about trebled. The P_2O_5 percentages, on the other hand, are consistently increased by lime, especially for the 1945 mangolds, where they are almost twice as high as for the control. As a result, the total P_2O_5 removal during 4 years is about trebled. These results, therefore, illustrate very clearly the beneficial effect of lime on phosphate availability. The percentage values show a slight but consistent trend in favour of magnesian lime compared with other forms, but this is not borne out by the uptake values over the 4 years which show the carbonate forms to be just as good. Lack of magnesium is not therefore an important factor governing phosphate availability in the Craigiebuckler soil. It is also apparent that the blast-furnace slag has no specific effect on phosphate availability and tends, if anything, to be less effective than the other forms.

Analytical data were also obtained for sodium and manganese, but they show no special feature and are not included. In general, lime gave lower percentages but higher total uptakes than the control.

The crop analyses for Wedderhill are somewhat less consistent than at Craigiebuckler, but present the same general picture. The general effect of lime is reflected much more in the uptake values than in the percentages; there is, for example, no appreciable increase in the P_2O_5 percentages which are occasionally lower in the presence of lime. The magnesian lime, Table 7, again shows a comparatively small effect on calcium-uptake but considerable increases in magnesium percentage and uptake. Apart from this there are no clear differences between forms and the main feature is the increased removal of other nutrients.

Soil data.—Some typical data from the Craigiebuckler experiment are given in Table 8. The over-all effect of the different rates of lime is marked and, especially after 2 years, the pH follows the CaO. In the earlier samplings both values show considerable inconsistencies, particularly for the coarser materials. These inconsistencies are doubtless the result of sampling errors and are to be expected because, initially, the samples consist of heterogeneous soil-lime mixtures. Considerable caution is therefore necessary in interpreting the results. Even so, the lower pH and CaO values for shell sand in the first sampling, particularly at the 35-cwt. rate, are probably real and indicate that this coarse material is slower-acting in the soil and more slowly soluble in acetic acid than the finer forms. The fact that its pH inferiority is more pronounced at the higher rate lends additional support to this conclusion, because such differences are more significant at higher pH values where the buffering is stronger. The pH values for the limestones in the first sampling when considered alone give no suggestion that the coarser sizes are slower-acting than the fine, but when they are considered in relation to CaO the 100-mesh material appears slightly superior to the other two and about equal to burnt lime. The only clear trend after one year is the consistent inferiority of the 52·5-cwt. rate of blast-furnace slag compared with burnt lime, in both pH and CaO, and on the whole

this material tends to give rather lower values than the other forms. It should also be noted that the pH values for the equivalent rates of magnesian lime and ordinary burnt lime agree very closely throughout, and that the 52·5-cwt. rate of burnt lime shows up very clearly in both pH and CaO.

The corresponding results from Wedderhill show the same general picture and are not included. After two years, the 30-cwt. rates of the various forms raised the pH from 5·1 to 6·2 at Wedderhill I, and from 5·0 to 5·7 at Wedderhill II, and both soils had a CaO value of about 0·45 per cent.

Data were also obtained for acetic-soluble MgO, K_2O, and P_2O_5 for the three soils. They show no consistent effect of lime on K_2O and P_2O_5, and the calcium forms did not affect the MgO. As would be expected, the rich magnesian lime increased the readily soluble MgO considerably, the 35-cwt. rate raising the Craigiebuckler value from 7 to about 40 mg. per 100 gm. soil, and the 30-cwt. rate raising the Wedderhill II value from 30 to about 90.

Discussion

The results illustrate very clearly that it pays to lime acid soils and that the differences between forms are quite unimportant compared with the benefits obtained. Blast-furnace slag tends to be slightly inferior to other forms and shows no specific silicate effect on phosphate availability in the present soils; but it is still an effective liming material and the possibility of using it should not be overlooked. This applies also to shell sand, which is a little slower-acting in the first year but otherwise equally effective as other forms.

Except for the above small differences there are no consistent variations between forms. The carbonate forms are just as good as burnt lime, and there is no clear evidence that the 20–40 mesh limestone is inferior to the finer sizes in the first year. There is likewise no conclusive evidence that it is superior in later years; the yield-trend is in this direction, but there is an opposite trend in calcium-uptake. Nearly all these trends, however, are of academic rather than practical significance. The results are in general agreement with those of Albrecht [6] in that they provide no justification for fine grinding of limestone. On the contrary, they indicate that a product with about 45 per cent. finer than 100-mesh and the remainder finer than 20 mesh, as suggested by Prof. G. W. Robinson, would be very suitable for Scottish conditions. This would be similar to the 'agricultural ground limestone' commonly used in America.

The burnt magnesian lime provides an effective means of increasing the magnesium-content of crops and is just as effective as calcium forms in correcting acidity. It shows no specific effect on phosphate availability in the present soils but, as suggested by Truog [7], it might well do so on soils relatively low in magnesium. The results for the low-grade magnesian limestone show little effect on the percentage MgO in the crops at Craigiebuckler, where magnesium deficiency is not a limiting factor. Richer materials should, therefore, be used if it is suspected

that low magnesium in crops may be affecting animal health. The single application of magnesian lime has shown no undesirable effect and the results provide no support for the prejudice against this form [5]. But they provide no information about the exclusive use of magnesian lime over a long period.

Another practical implication of the results concerns the amount of lime to apply. The crop data for Craigiebuckler and Wedderhill I indicate comparatively little response above 15–17·5 cwt. CaO per acre and none above 30–35 cwt. Since losses in the drainage are relatively higher at high lime-levels, dressings higher than about 35 cwt. CaO per acre would appear to be uneconomical on soils such as these. The 52·5-cwt. rate of burnt lime raised the pH of the Craigiebuckler soil to 6·5–7·0 compared with about 6·0 for the 35-cwt. rate but produced no additional effect on crops. The results, therefore, support the normal practice for a rotation of oats, roots, hay, and pasture, of liming ordinary mineral soils to a pH of 6·0–6·2, which corresponds to a CaO-content of about 0·25 per cent. The 30-cwt. rates at Wedderhill I also gave a pH of about 6·0 and the CaO value of about 0·45 per cent. when corrected for the lower volume weight is comparable with that for Craigiebuckler. The soil at Wedderhill II has a still higher organic-matter content and buffer capacity, and in agreement with this shows a lower pH of 5·7 for the 30-cwt. rates. On the weight basis the CaO value is much the same as for Wedderhill I but on the volume basis is relatively lower. These lower values, however, do not of necessity mean that the Wedderhill II soil would have continued to respond above the 30-cwt. CaO rate used. Experience shows that a lower pH value is desirable in this peaty type of soil and that the acetic-soluble CaO is not an adequate measure of the calcium status.

Finally, the results illustrate that liming markedly increases the removal of other nutrients in the crops and serve to emphasize the need for adequate supplementary manuring.

Summary

1. The effectiveness of ground burnt lime, ground burnt magnesian lime, ground magnesian limestone, dried paper-works lime, calcareous shell sand, blast-furnace slag, and various sizes of ground limestone, has been tested in three field experiments carried out over 4 years.

2. All forms produced large crop responses and marked increases in soil pH and acetic-soluble CaO. Except where the yield response was very high, the percentage CaO in the crops was also increased, and there were greatly increased removals of other nutrients, especially phosphate.

3. Compared with the general effect of lime all the differences between forms were unimportant, but blast-furnace slag was slightly inferior to the others and shell sand was appreciably slower-acting in the first year. Otherwise there was no other consistent difference, and the carbonate forms were just as effective as burnt lime.

4. The 20–40 mesh limestone was highly effective throughout and the results provide no support for fine grinding. A product with about 45

per cent. finer than 100 mesh and the remainder finer than 20 mesh would be fully adequate under Scottish conditions.

5. Burnt magnesian lime markedly increased the magnesium-content of the crops but low-grade magnesian limestone did not. Both were equally effective as other forms in correcting acidity and increasing yields.

6. The results support the normal practice of liming ordinary mineral soils to a pH of 6·0–6·2, corresponding to an acetic-soluble CaO of about 0·25 per cent. for a common rotation of oats, roots, hay, and pasture. They also illustrate very clearly the benefits of liming and the need for adequate supplementary manuring.

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TABLE 1. *Reference Symbols and Analyses of Liming Materials*

Symbol	*Material*	CO_2 *per cent.*	*CaO per cent.*	*MgO per cent.*
1. G.B.L. . .	Ground burnt lime	1·2	87·3	2·3
2. G.B.M.L. .	Ground burnt magnesian lime	6·7	48·0	31·8
3. P.W.L. .	Dried paper-works lime	40·4	50·5	0·5
4. S.S. . .	Calcareous shell sand (John o'Groat's)	41·4	51·5	1·1
5. G.L. . .	Ground limestone 70 per cent. fineness	42·6	51·7	1·8
6. G.L. 20–40 .	Ground limestone <20>40 mesh	41·7	53·1	0·5
7. G.L. 40–100 .	Ground limestone <40>100 mesh	40·1	52·3	0·6
8. G.L. 100 .	Ground limestone <100 mesh	38·7	52·5	1·3
9. G.M.L. . .	Ground magnesian limestone	42·4	44·8	5·9
10. B.F.S. . .	Blast-furnace slag	..	48·6	2·6

TABLE 2. *Mean Yield Data for Ground Burnt Lime, Ground Burnt Magnesian Lime, Three Sizes of Ground Limestone, Ground Magnesian Limestone, Shell Sand, Paper-works Lime, and Blast-furnace Slag at Craigiebuckler*

All CaO rates and yields are in cwt. per acre.

Material	*CaO rate*	*1944* Rye-grass and red clover*	*1945* Mangold bulbs*	*1946 Barley grain*	*1947 Barley grain*	*1948 Mixed hay*
..	0	13·7	64	11·6	8·7	32·8
1. G.B.L. . .	52·5	22·8	432	24·1	18·5	41·9
1. G.B.L. . .	35·0	23·4	387	26·5	19·8	42·0
1. G.B.L. . .	17·5	19·8	356	24·2	17·3	42·5
1. G.B.L. . .	8·75	14·1	230	20·3	13·6	31·5
2. G.B.M.L. . .	35·0	19·3	454	25·7	18·5	44·0
2. G.B.M.L. . .	17·5	17·3	380	21·0	18·0	40·1
6. G.L. 20–40 .	35·0	16·9	415	25·5	19·4	49·5
7. G.L. 40–100 .	35·0	25·9	452	26·9	19·1	46·9
8. G.L. 100 . .	35·0	20·4	429	26·1	20·4	45·8
6. G.L. 20–40 .	17·5	19·1	391	24·3	19·7	49·6
7. G.L. 40–100 .	17·5	18·1	342	25·3	15·3	42·8
8. G.L. 100 . .	17·5	22·6	370	17·0	16·8	39·4
9. G.M.L. . .	35·0	19·3	449	24·0	18·9	46·5
4. S.S. . . .	35·0	16·5	421	26·1	19·1	48·5
4. S.S. . . .	17·5	15·5	331	22·5	17·9	42·2
3. P.W.L. . .	35·0	19·4	499	25·0	19·3	48·8
3. P.W.L. . .	17·5	20·4	383	23·5	16·3	41·6
10. B.F.S. . .	52·5	18·1	432	26·5	20·9	48·2
10. B.F.S. . .	35·0	19·6	373	23·4	16·3	44·3
10. B.F.S. . .	17·5	22·9	308	22·7	17·1	43·1
S.E. of single mean ±†	..	2·52	35·6	1·61	1·28	3·18

* The yield and analytical data for all crops except turnips and mangolds refer to oven-dry matter (80° C.). The turnip and mangold data are for fresh matter.

† Since there were three no-lime plots in each lattice square the standard error of the no-lime mean is different from that for the individual lime treatments.

TABLE 3. *Crop Analyses for Craigiebuckler corresponding to Yield Data in Table 2.*

All Uptake data are in lb. per acre. F.M. = Fresh Material; D.M. = Dry Matter (80° C.)

Material	*CaO rate*	*1945 Mangold bulbs*		*1946 Barley grain*		*1947 Barley grain*		*1948 Mixed hay*		*Total uptake 1945–8*
		Per cent. in F.M.	*Uptake*	*Per cent. in D.M.*	*Uptake*	*Per cent. in D.M.*	*Uptake*	*Per cent. in D.M.*	*Uptake*	
					CaO					
..	0	0·050	3·6	0·059	0·8	0·060	0·6	0·44	16·2	21·2
Mean of Ca forms .	35	0·029	13·9	0·079	2·2	0·060	1·3	0·84	43·8	61·2
2. G.B.M.L. . .	35	0·018	9·1	0·054	1·6	0·051	1·1	0·54	26·6	38·4
					MgO					
..	0	0·029	2·1	0·18	2·3	0·16	1·6	0·22	8·1	14·1
Mean of Ca forms .	35	0·021	9·4	0·20	5·5	0·19	3·9	0·25	12·2	31·0
2. G.B.M.L. . .	35	0·028	14·2	0·23	6·6	0·28	5·8	0·57	28·1	54·7
9. G.M.L. . . .	35	0·021	10·6	0·19	5·1	0·17	3·6	0·38	19·8	39·1
					K_2O					
..	0	0·39	28·0	0·66	8·6	0·74	7·2	1·95	71·6	115·4
Mean of all forms .	35	0·42	193·8	0·70	20·0	0·76	15·8	1·61	80·1	309·7
					P_2O_5					
..	0	0·029	2·1	0·71	9·2	0·77	7·5	0·40	14·7	33·5
Mean of all forms .	35	0·052	24·3	0·90	25·5	0·89	18·6	0·44	22·0	90·4

TABLE 4. *Mean Yield Data for Three Sizes of Ground Limestone and Ground Burnt Lime at Wedderhill I*

Material	*CaO rate*	*1944 Turnips*	*1945 Barley grain*	*1946 Mixed hay*	*1947 Mixed hay*
..	0	320	14·1	18·5	26·8
6. G.L. 20–40 . .	30	330	12·4	36·3	46·6
7. G.L. 40–100 . .	30	347	12·5	33·2	51·2
8. G.L. 100 . .	30	359	12·3	34·0	44·8
1. G.B.L. . . .	30	343	12·3	32·3	46·2
1. G.B.L. . . .	15	342	13·8	29·4	41·5
S.E. of single mean ± .	..	..	0·75	1·91	3·39

TABLE 5. *Crop Analyses for Wedderhill I corresponding to Yield Data in Table 4*

Material	CaO rate	1945 Barley grain		1946 Mixed hay		1947 Mixed hay		Total uptake 1945–7
		Per cent. in D.M.	Uptake	Per cent. in D.M.	Uptake	Per cent. in D.M.	Uptake	
				CaO				
..	0	0·060	0·9	0·61	12·6	0·77	23·1	36·6
Mean of Ca forms .	30	0·065	0·9	0·91	34·5	0·73	38·5	73·9
				MgO				
..	0	0·21	3·3	0·20	4·1	0·27	8·1	15·5
Mean of Ca forms .	30	0·27	3·7	0·29	10·8	0·21	11·2	25·7
				K_2O				
..	0	0·75	11·8	2·08	43·1	2·09	62·7	117·6
Mean of Ca forms .	30	0·80	11·0	2·14	81·4	1·48	73·3	170·7
				P_2O_5				
..	0	1·11	17·5	0·55	11·4	0·51	15·3	44·2
Mean of Ca forms .	30	1·16	16·1	0·52	19·7	0·41	21·8	57·6

TABLE 6. *Mean Yield Data for Ground Limestone, Shell Sand, Paperworks Lime, Ground Burnt Magnesian Lime, and Blast-furnace Slag at Wedderhill II*

Material	CaO rate	1944 Turnips	1945 Barley grain	1946 Mixed hay	1947 Mixed hay
..	0	345	10·1	18·6	26·8
5. G.L. . .	30	362	10·4	35·0	49·3
4. S.S. . . .	30	384	10·2	35·8	47·9
3. P.W.L. . .	30	368	11·4	30·5	48·6
2. G.B.M.L. . .	30	386	11·9	34·3	46·8
10. B.F.S. . .	30	352	11·7	34·5	49·5
S.E. of single mean ±.	..	..	..	1·55	2·58

TABLE 7. *Crop Analyses for Wedderhill II corresponding to Yield Data in Table 6*

Material	CaO rate	1945 Barley grain		1946 Mixed hay		1947 Mixed hay		Total uptake 1945–7
		Per cent. in D.M.	Uptake	Per cent. in D.M.	Uptake	Per cent. in D.M.	Uptake	
				CaO				
..	0	0·055	0·6	0·54	11·3	0·57	17·1	29·0
Mean of Ca forms .	30	0·063	0·8	0·65	24·7	0·52	28·4	53·9
2. G.B.M.L. . .	30	0·075	1·0	0·49	18·8	0·27	14·2	34·0
				MgO				
..	0	0·26	2·9	0·23	4·8	0·18	5·4	13·1
Mean of Ca forms .	30	0·27	3·3	0·26	9·9	0·18	10·0	23·2
2. G.B.M.L. . .	30	0·25	3·3	0·41	15·8	0·27	14·2	33·3
				K_2O				
..	0	0·76	8·6	2·22	46·3	1·96	59·1	114·0
Mean of all forms .	30	0·77	9·7	2·21	83·9	1·27	69·1	162·7
				P_2O_5				
..	0	1·22	13·8	0·50	10·4	0·49	14·7	38·9
Mean of all forms .	30	1·24	15·5	0·51	19·3	0·37	20·2	55·0

TABLE 8. *Mean Soil Data for Craigiebuckler*

Material	CaO rate	13.7.44		5.4.45		18.3.46		22.7.48	
		pH	% CaO*	pH	% CaO	pH	% CaO	pH	% CaO
..	0	5·0	0·13	5·5	0·11	5·3	0·11	5·1	0·10
1. G.B.L. . .	52·5	6·3	0·37	7·0	0·65	6·5	0·36	6·4	0·33
1. G.B.L. . .	35·0	5·9	0·33	5·9	0·22	6·0	0·22	5·8	0·24
1. G.B.L. . .	17·5	5·7	0·30	6·1	0·24	5·7	0·18	5·6	0·20
1. G.B.L. . .	8·75	5·4	0·15	5·5	0·12	5·4	0·13	5·4	0·13
2. G.B.M.L. .	35·0	6·0	0·22	6·0	0·16	6·0	0·17	5·8	0·19
2. G.B.M.L. .	17·5	5·6	0·15	6·0	0·16	5·7	0·13	5·5	0·13
6. G.L. 20–40 .	35·0	6·0	0·56	6·5	0·69	5·9	0·25	5·9	0·23
7. G.L. 40–100 .	35·0	6·3	0·63	6·7	0·53	6·1	0·29	6·1	0·23
8. G.L. 100 .	35·0	6·1	0·39	6·1	0·30	6·0	0·25	6·1	0·23
6. G.L. 20–40 .	17·5	5·7	0·35	6·2	0·32	5·6	0·17	5·7	0·15
7. G.L. 40–100 .	17·5	5·6	0·26	6·5	0·44	5·7	0·20	5·5	0·14
8. G.L. 100 .	17·5	6·4	0·35	6·1	0·25	5·7	0·19	5·6	0·17
9. G.M.L. .	35·0	6·4	0·45	6·4	0·29	6·1	0·27	5·8	0·20
4. S.S. . .	35·0	5·6	0·29	6·2	0·34	5·8	0·20	5·9	0·23
4. S.S. . .	17·5	5·5	0·26	5·7	0·19	5·6	0·19	5·5	0·19
3. P.W.L. . .	35·0	6·6	0·44	6·8	0·39	6·2	0·26	5·8	0·23
3. P.W.L. . .	17·5	5·8	0·21	6·1	0·24	5·6	0·17	5·4	0·16
10. B.F.S. . .	52·5	5·7	0·29	6·4	0·36	5·9	0·24	5·8	0·24
10. B.F.S. . .	35·0	5·4	0·23	6·3	0·37	5·7	0·20	5·6	0·20
10. B.F.S. . .	17·5	5·4	0·20	5·7	0·16	5·5	0·15	5·3	0·14

* The CaO values were obtained by extracting 20 gm. air-dry soil with 800 ml. 2·5 per cent. acetic acid for 2 hours.

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